THE UNIVERSITY OF ALBERTA

THE COEFFICIENT OF THERMAL EXPANSION OF CONCRETE

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The undersigned certify that they have read and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled

THE COEFFICIENT OF THERMAL EXPANSION OF CONCRETE

submitted by Harry Gerard Basler, B.Sc.

in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Measurements of the thermal expansion of various strengths of relatively dry Portland cement concretes, which were prepared from some common Alberta aggregates, have been made over the temperature range -37°F to +97°F by means of electrical resistance strain gages and a demountable mechanical strain gage.

Results indicated that these concretes possessed mean thermal coefficients which ranged from 4.6 to 6.1 micro-inches per inch per degree Fahrenheit. Within the limits of the investigation, the thermal coefficient appeared to increase with temperature.

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INTRODUCTION

The thermal coefficient of expansion of concrete has been generally assumed to be in the order of 6.0×10^{-6} inches per inch per degree Fahrenheit or close to that of structural and reinforcing steels. This assumption has proven to be quite satisfactory in most reinforced concrete structures, but it has been pointed out (15) that failures in structures of composite steel and concrete construction could occur because of the invalidity of this assumption or at least because of the inaccurate evaluation of the magnitude of the difference between the thermal coefficient of concrete and that of steel.

Early investigations (1) into the thermal coefficient of expansion of concrete, which were conducted near the beginning of the use of reinforced concrete construction, indicated that the coefficient was close to that of steel. This led to the general belief which is held by some engineers even today, that concrete has the same coefficient regardless of the choice of aggregates or cement. Numerous investigations of more recent date have shown that the thermal coefficient of expansion of concrete is in fact a variable quantity ranging from 1.7 to 8.0.(*) It is dependent primarily upon the source and nature of the aggregate, the richness of mix,

(15) Numbers in parenthesis refer to the list of references in the bibliography.

* Micro-inches per inch per degree Fahrenheit to be understood throughout this manuscript.

the temperature range, and the degree of saturation (particularly below the freezing point of water).

The present program was initiated to study the thermal expansion of Portland cement concrete as prepared from some of the more common Alberta aggregates.

HISTORICAL REVIEW

Since the turn of the century, various investigations have been performed to evaluate the thermal expansion (*) characteristics of concrete. It is understandable that these investigations differed greatly in scope and not all of them have extended their study to include temperatures below the freezing point of water. Since there is a marked change in the thermal expansion characteristics of concrete upon freezing, this review is divided into two parts; namely, behavior above freezing and behavior below freezing. Length changes which occur as a result of temperature changes below the freezing point of water are complicated by the conversion of water to ice within the pore system of the concrete. Therefore, investigations including a study of this, will be treated separately.

Behavior Above Freezing

A considerable variation in the magnitude of the thermal coefficient of expansion has been reported by various investigators (1, 3, 4, 7, 10, 12). Values reported range from as low as 1.7 to as high as 8.0.

The coefficient is known to vary with the cement, temperature, and the mineralogy of the aggregate, as well as with the richness of mix, curing conditions, moisture content, and the age of the concrete.

* Hereafter the word "expansion" will be used in a general sense; that is, it may be positive or negative.

Several investigations (2, 4, 7, 10, 12, 13) into the coefficient of thermal expansion of concrete aggregates have disclosed values ranging from 1.2 for limestone to 9.7 for feldspar. Mitchell (12), in particular, reported that the coefficient of thermal expansion of a certain rock type depends on the source as well as the type of aggregate. The coefficient for limestone, for example, has been observed to range from 1.2 to 6.5. Mitchell also observed that most rocks which consist of a single crystal or mass of crystals with similar orientation exhibit thermal anisotropy. These variations in the properties of the aggregate eliminate the possibility of any quantitative correlation of the aggregate type and the thermal expansion of concrete, but qualitative comparisons can and have been made successfully. Several investigators (4, 7, 10, 12) have shown that the thermal coefficient for concrete increases as the thermal coefficient of the aggregate increases.

Tests (2, 12) on mortars have shown coefficients which ranged from 3.6 to 7.0. Concrete prepared from aggregate and mortar of considerably different thermal coefficients could be made particularly vulnerable to frost action because of the high internal stresses produced at low temperatures. Callan (9) pointed out that differences in the order of 3.0 between mortar and aggregate could initiate failure. A failure in otherwise sound concrete reported by Pearson (5) has been attributed solely to this cause.

The coefficient of expansion of neat Portland cement has been shown to vary from 5.1 to 12.5 (1, 3, 10, 12). Extensive long-term tests on neat Portland cements reported by Meyers(3) indicated that

under constant storage conditions, the coefficient increased with the tricalcium silicate content of the cement and with age for about the first 18 months. At greater ages, the coefficient decreased gradually. Findings by Mitchell (12) and Meyers (3) were generally in direct agreement with respect to the effects of tricalcium silicate at early ages, but neither Mitchell (12) nor Bonnel (10) could establish any significant trend with respect to age alone for concrete under constant curing conditions.

Mitchell (12) found that the thermal coefficient of neat cement increased with the degree of saturation until some optimum moisture content (80% to 90% of vacuum saturation) was reached. The results published by Meyers(3) are generally in agreement in this respect. A probable explanation for this behavior was given by Powers (6), who indicated that the water absorption and swelling pressure of cement gel, at a given relative humidity, may vary with temperature and produce an apparent additional thermal expansion.

For concrete, the effects of age, moisture content, and curing conditions must be manifested in the cement paste. In view of the combined findings with regard to the thermal expansion characteristics of cement paste, it is not surprising that:

a) Meyers (3) and Keil (4) found that the thermal coefficient of concrete, under constant curing conditions, increased with age.

b) Meyers (3) and Bonnel (10) reported that storing in water or steaming produced an increase in the thermal coefficient.

c) Meyers (3) and Bonnell (10) found that dessication of concrete produced a decrease in the thermal coefficient.

d) Mitchell (12) observed that as the moisture content was increased, the thermal coefficient increased.

The changes in the thermal coefficient due to these causes were generally reported to be in the order of 1.0 micro-inch per inch per degree Fahrenheit.

The thermal coefficient of expansion for cement paste is generally greater than that of the aggregates. This is the direct cause of the observation made by several investigators that the coefficient of expansion of concrete increases with the richness of mix.

Hatt (1) reported that the length-temperature relationship for concrete was non-linear. A similar but far more pronounced relationship for limestone was observed by Willis and DeReus (2). Mitchell (12) and Bonnel (10) observed that the relationship for neat cement was markedly non-linear. The latter two observations are probably linked with the first.

Weiner (7) observed that the addition of an air entraining agent did not materially affect the thermal properties of concrete above freezing. Mitchell (12) attributed the slightly different thermal expansion characteristics of air entrained concrete, as compared to plain concrete, to a difference in the ease with which the concrete becomes saturated with water and the degree of actual saturation. The effect of air entrainment on the thermal properties of concrete at temperatures below freezing are entirely different from those above freezing. This was pointed out by Powers (11).

Behavior Below Freezing

The thermal expansion characteristics of concrete at temperatures below freezing depend primarily upon the moisture content of the concrete. An extensive study of volume changes in concrete during freezing and thawing was made by Valore (8). The investigation included a study of the degree of saturation and the rate of temperature change. Mitchell (12) later made a similar study but investigated the degree of saturation in more detail and did not emphasize the effects of the rate of temperature change.

The results of both of these investigations were in agreement where they overlapped and the combined findings follow:

a) The thermal expansion relationship was nearly linear for air dry concrete and independent of the rate of temperature change. For such concrete the thermal expansion characteristics were much the same as above freezing.

b) The thermal expansion relationship for partially saturated concrete below "critical saturation" was generally not independent of the rate of temperature change, and showed departures from linearity. These departures were believed to be the effects of the conversion of water to ice within the pore structure of the concrete and were least pronounced for slow cooling.

c) Concretes with moisture contents at critical saturation or above, expanded at some temperature below freezing to which the pore water had supercooled. This expansion started at some temperature between 23°F and 27°F and averaged at 24°F. This action produced a definite upward surge of the length-temperature curve which did not

[illegible]

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The results of both of these investigations were in agreement where they overlapped and are summarized as follows:

a) The thermal expansion relationship was nearly linear for air dry concrete and independent of the rate of temperature change. For such concrete the thermal expansion characteristics were much the same as above freezing.

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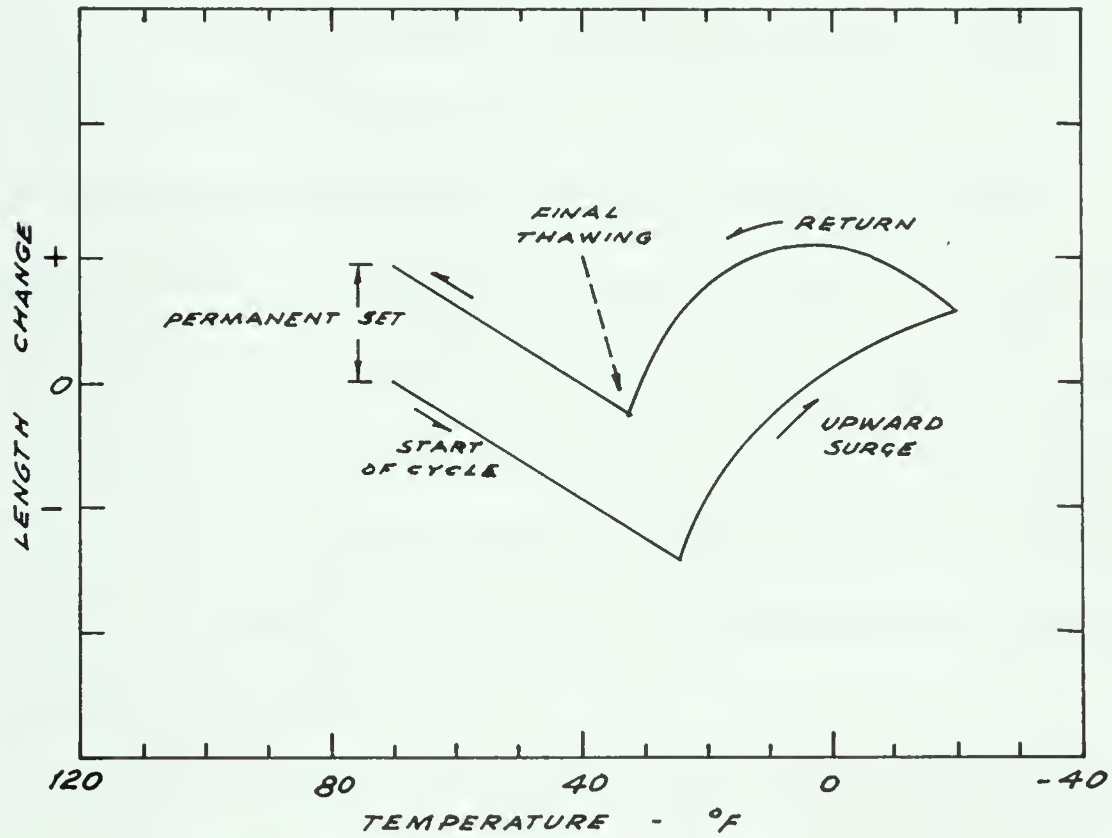
c) [illegible]

return to indicate final thawing until the temperature had returned to 32°F or above. When the concrete temperature was returned to 70°F, an upward displacement or "permanent set" was evident. This displacement was usually less than the freezing expansion. The typical behavior is shown in Figure 1.

FIGURE 1



TYPICAL LENGTH-TEMPERATURE RELATIONSHIP FOR CONCRETES WITH MOISTURE CONTENTS ABOVE CRITICAL SATURATION

d) During slow cooling, the pore water in virgin concrete supercooled before it froze. There was no evidence of supercooling during a fast cycle.

e) Air entrained concretes had a lower percentage of apparent saturation after a given curing process and were more difficult to saturate completely even under a vacuum than were plain concretes.

The difference between plain and air entrained concretes appeared to be limited to the effects of the rather marked difference in the degree of saturation. The slight difference in diffusivity in air entrained concrete, as compared to plain concrete, had only negligible effects upon the thermal characteristics (7).

The phenomena observed by Valore (8) and Mitchell (12) were clearly explained by Powers (11) in terms of the behavior of water in the air voids and capillary pores of the cement paste. The behavior was explained as follows:

> "Water freezing in capillary cavities produces hydraulic pressure and consequent dilation. At any temperature below the temperature at which the ice in the cavity was formed, gel water can diffuse to that cavity and cause the ice body to grow, producing expansion. Since diffusion is slow, expansion is due mainly to hydraulic pressure when freezing is rapid.
>
> "When air voids are present they limit the hydraulic pressure according to the thickness of the layers of paste between them. Also, the ice they contain draws water from the paste, causing the paste to shrink. Since the ice in the capillary cavities generally has a higher free energy than that in the voids, the ice in the air voids may eventually draw the excess from both the gel and the frozen cavities, producing an over-all contraction. Expansion due to growth of ice in the capillary cavities is prevented if the air voids are close enough together, as

is also expansion due to hydraulic pressure.

"During thawing, the water that was extracted from the paste by ice in the air voids diffuses back. In a paste free of air voids, the ice in the capillary cavities melts progressively, and water drawn from the gel during freezing is returned to the gel.

"The function of the air voids is to limit hydraulic pressure and to limit the time during which capillary ice can increase by diffusion of gel water. The spacing factor controls the effectiveness of the voids for either mechanism."

CHAPTER I

SCOPE

The intention of this program was to study the thermal expansion of Portland cement concretes prepared from Alberta materials in an effort to reveal any unusual coefficient of thermal expansion which might be exhibited by these concretes. It was further intended to furnish information regarding the influence of concrete strength and aggregate source upon the coefficient of thermal expansion, to compare the thermal coefficients of these concretes with that of steel, and to provide thermal expansion data for use in concrete design and highway research dealing with these concretes.

To accomplish these ends, coarse and fine aggregates were obtained from three sources, tested, and combined according to the source with Type I Normal Portland Cement and water in proportions to yield five strengths of concrete for each source. In addition, a fine aggregate of inferior quality (very fine) was obtained from one of the sources and combined with the corresponding coarse aggregate, cement and water to produce two strengths of concrete.

For each concrete strength, three cylindrical specimens, 3-1/2 inches in diameter by 10 inches in length, for thermal expansion measurements and four compression test cylinders, 6 inches in diameter by 12 inches in length, were cast from a single pour. The large cylinders were tested in compression after twenty-eight days of moist curing. The small specimens were moist cured for twenty-eight days after which they were given an air drying treatment to render moisture

contents well below critical saturation (12). The drying treatment was kept as constant as possible for all specimens in order to afford a comparison which would not involve the moisture variable.

Two samples of a number 8 steel reinforcing bar, 10 inches long, of the same lot as used in the experimental concrete road situated in Bowness, Alberta, were obtained and the thermal coefficient of expansion determined.

Length changes due to temperature changes were measured for intervals within the range -40°F to +100°F during a slow test (8) by means of "SR-4" strain gages and a demountable mechanical (Demec) strain gage.

CHAPTER II

MATERIALS

General Description

Coarse and fine aggregates were obtained from three sources during the summer of 1959:

a) Precast Concrete Ltd., Edmonton, Alberta.

The coarse and fine aggregates originated as natural deposits near Onoway and Fort Saskatchewan, Alberta, respectively.

b) Precast Concrete Ltd., Calgary, Alberta.

The aggregates originated at a pit at Ogden, Alberta.

c) Peerless Rock Ltd., Calgary, Alberta.

The aggregates originated at a pit just west of Calgary and were the same as those used in the experimental test road situated in Bowness, Alberta. The fine aggregate of inferior quality, referred to previously, was also obtained here.

The cement was Type I, Normal Portland cement; obtained from and manufactured by the Inland Cement Company Ltd., Edmonton, Alberta. The cement was taken in one lot from Silo C-2 on August 5th, 1959.

The mixing water was taken directly from the Edmonton City water main.

Two samples of a number 8 steel reinforcing bar were obtained from the same lot as had been used in the experimental test road situated in Bowness, Alberta. These steel samples were to be used for purposes of comparison.

Physical Properties of Coarse Aggregates

The physical properties and grading of the coarse aggregates were determined in accordance with A.S.T.M. specifications (17) and are given in Tables 1 and 2. Each reading is the average of a minimum of three tests. The variation in results was well within the A.S.T.M. limits where specified. The A.S.T.M. requirements were met by all of the coarse aggregates.

Table 1

Physical Properties of Coarse Aggregates

Property	Precast Concrete, Edmonton	Precast Concrete, Calgary	Peerless Rock, Calgary
Dry Unit Weight Lbs./Cu.Ft.	103.0	104.0	101.4
Bulk * Specific Gravity	2.51	2.65	2.64
Absorption % by Weight	1.35	0.76	0.81
Lightweight ≠ Pieces % by Weight	0.1	0.0	0.0

* Saturated surface dry basis.

≠ Heavy liquid-carbon tetrachloride only.

Table 2

Grading of Coarse Aggregate

Aggregate	% Passing Screen Indicated				
	1	3/4	1/2	3/8	1/4
Precast, Concrete, Edmonton	100	71.4	41.4	30.2	1.8
Precast Concrete, Calgary	100	77.7	40.5	25.7	1.8
Peerless Rock, Calgary	100	76.6	29.6	16.0	0

Physical Properties of Fine Aggregates

The physical properties and grading of the fine aggregates were determined in accordance with A.S.T.M. (1958) specifications (17) and are listed in Tables 3 and 4. Each value in Table 3 is the average of three tests. The variation in the results for each set of tests was well within the limits specified by the A.S.T.M.

Table 3

Physical Properties of Fine Aggregates

Property	Precast Concrete, Edmonton	Precast Concrete, Calgary	Peerless Rock, Calgary FM 2.97	Peerless Rock, Calgary FM 1.97
Organic Impurities (Color)	#4 (coal)	#1	#2	#2
Dry Unit Weight Lbs./Cu.Ft.	99.5	106.4	100.3	90.7
Bulk * Specific Gravity	2.62	2.62	2.67	2.68
Absorption % by Weight	0.69	1.05	1.20	1.37
Lightweight ≠ Pieces % by Weight	0.00	0.00	0.00	0.02

* Saturated surface dry basis.

≠ Heavy liquid - carbon tetrachloride only.

Table 4

Grading of Fine Aggregates

Aggregate	% Passing Screen Indicated							
	4	8	16	30	50	100	200	F.M.
Precast	98.5	97.2	94.7	75.9	8.3	0.6		2.25
Concrete,	97.9	96.9	94.4	75.0	9.2	0.8		2.26
Edmonton	97.1	95.7	93.3	74.3	9.5	0.9		2.29
Precast	98.6	85.8	73.7	61.9	26.8	4.2	2.1	2.49
Concrete,	98.8	85.8	74.1	62.3	26.8	4.2	2.3	2.48
Calgary	98.3	85.3	73.6	62.0	27.2	4.4	2.7	2.49
Peerless	97.9	78.8	61.6	42.9	17.3	6.7	3.5	2.95
Rock,	97.5	79.2	61.9	43.0	17.2	6.7	3.4	2.95
Calgary	98.1	78.0	60.9	42.0	16.6	6.4	3.4	2.98
(FM 2.97)								
Peerless	96.9	96.0	94.9	89.2	22.3	2.0	0.9	1.99
Rock,	97.2	96.1	95.1	89.4	22.1	1.9	0.9	1.98
Calgary	98.0	96.9	95.9	90.3	22.5	2.1	1.1	1.94
(FM 1.97)								

Physical and Chemical Properties of Cement

The physical properties and chemical composition of the Type I Normal Portland cement which was used in the preparation of all concrete specimens are listed in Tables 5 and 6. The data were determined by the technical staff of the Inland Cement Company Ltd.

Table 5

Chemical Composition of Cement

Loss on ignition		0.60	
Silicon Dioxide	(SiO_2)	23.10	
Aluminum Oxide	(Al_2O_3)	5.40	
Ferric Oxide	(Fe_2O_3)	2.90	
Calcium Oxide, Total	(CaO)	63.60	
Magnesium Oxide	(MgO)	3.00	
Sodium Oxide	(Na_2O)	0.12	
Potassium Oxide	(K_2O)	0.28	
Sulphur Trioxide	(SO_3)	1.92	1.90
Free Lime	(CaO)	1.30	1.63

Table 6

Physical Properties of Cement

Fineness Blaine	(cm^2/gm)		3111	3088
Normal consistency	(%)		25.6	25.0
Time of setting (in Hrs.: Mins.)	(a)	Initial	2:30	3:00
	(b)	Final	4:30	5:05
Flow Table Test	(%)		108	108
Compressive strength (in p.s.i.)	(a)	3 days	2600	2330
	(b)	7 days	4490	4160
	(c)	28 days	6575	6190
Tensile strength (in p.s.i.)	(a)	3 days		305
	(b)	7 days		445
	(c)	28 days		585
Autoclave expansion	(%)		0.144	0.079
False set	(mm.penetration)		48	48

CHAPTER III

PREPARATION AND PROCESSING OF SPECIMENS

Aggregates were obtained by random sampling and shipped in 70-pound silt-tight bags. In order to obtain a high degree of uniformity, the coarse aggregates were spread on the laboratory floor and room dried for 48 hours, divided into five size fractions (Table 2) by hand screening, and recombined by weight in the appropriate proportions. Fine aggregates were thoroughly mixed by hand in a moist condition and oven dried for about 24 hours at 100°C.

The concrete mixes were designed according to the proposed practice recommended by Committee 613 of The American Concrete Institute (16). Trial mixes were batched on this basis, and adjustments of the mixing water and cement factor were made to obtain the desired workability without altering the recommended water-cement ratio. All mixes had a properly sanded appearance, and no adjustments were necessary in the coarse and fine aggregate proportions. When the proportions necessary for the desired workability had been determined, trial cylinders were cast from a fresh batch of concrete and tested in compression after seven days of moist curing. This was done according to the A.S.T.M. specifications (17). On the basis of the results of the compression tests, adjustments were made in the water-cement ratio when necessary. That is, if the seven-day strengths fell consistently below 60 to 70 percent of the expected 28-day strengths (18), then the water-cement ratio was increased accordingly in the design of the final mix proportions. This was

found to be the case only with the concretes prepared from the Edmonton aggregates. It is of interest to note that this procedure did not seem to be justified; that is, the 28-day strengths which were finally obtained (see Table 7) were generally high. The final mixes were then designed using the A.C.I. recommendations with the water and water-cement ratios altered where necessary. An example of the method of design is shown in Appendix I.

Five strengths of concrete (3000, 3500 , 4000, 4500 , and 5000 p.s.i.) for each aggregate combination were designed and prepared on the foregoing basis, with the exception that only two strengths (3000 and 5000 p.s.i.) were prepared for the Peerless Rock aggregate combination in which the inferior quality fine aggregate (F.M. 1.97) was used. Two strengths were considered sufficient to give an indication of the thermal expansion properties of this low grade concrete. No attempt was made to decrease the water-cement ratio below the A.C.I. recommended value in an effort to obtain the 5000 p.s.i. 28-day compressive strength in this case.

For each strength of concrete, three cylindrical specimens, 3-1/2 inches in diameter by 10 inches were cast for thermal expansion measurements and four standard cylinders, 6 inches in diameter by 12 inches, for the compressive strength determinations. The mix proportions and compressive strengths are tabulated in Table 7.

Specimen Identification:

The following notations were used to identify the specimens according to the aggregates used and the design strengths:

E	-	Edmonton aggregate, Precast Concrete Ltd.
C	-	Calgary aggregate, Precast Concrete Ltd.
R'	-	Calgary aggregate, Peerless Rock Ltd., Using the coarse (F.M. 2.97) fine aggregate.
R	-	Calgary aggregate, Peerless Rock Ltd., Using the fine (F.M. 1.97) fine aggregate.
3	-	3000 p.s.i. 28-day design compressive strength.
3.5	-	3500 p.s.i. 28-day design compressive strength.
4	-	4000 p.s.i. 28-day design compressive strength.
4.5	-	4500 p.s.i. 28-day design compressive strength.
5	-	5000 p.s.i. 28-day design compressive strength.

For example, consider R'4.5. The R' denotes that Calgary aggregates from Peerless Rock Ltd., using the fine aggregate of high Fineness Modulus, were employed in the mix. The 4.5 denotes that the concrete was designed to have a 28-day strength of 4500 p.s.i. in compression.

Mix Proportions and Strengths

The mix proportions and 28-day compressive strengths obtained for the standard *, moist cured, 6" by 12" control cylinders are given in Table 7. The mix proportions listed are based upon dry weights and were adjusted before mixing to allow for the moisture content and absorption of the aggregates.

The compressive strengths obtained were not all close to the strengths for which the concretes were designed. An adequate range in strengths was the main feature sought and obtained for each aggregate type.

Slump measurements are not recorded. Adjustments in mix proportions were based upon the water-cement ratio and trial cylinders and not slump. Furthermore, the aggregates were relatively dry, with moisture contents below the saturated surface dry condition. When the trial mix did not exhibit the desired workability (2" to 3" apparent slump), the quantity of cement paste was changed so that a known water-cement ratio was maintained.

Specimen Manufacture

Molds for the 3-1/2 inch by 10 inch test specimens were fabricated to meet A.S.T.M. recommendations by splitting a seamless steel tube lengthwise, and welding a lug on the bottom of each section to provide for bolting to a thick steel base plate. A hose clamp was

* A.S.T.M. procedure in preparation and testing.

Table 7

Mix Proportions and Concrete Strengths

Concrete Type	W/C Gal./Bag*	Cement Factor Bags/Cu. Yd.	Mix Proportions for One Cubic Foot - Pounds				Ultimate ≁ 28-Day Compressive Strength p.s.i.
			Cement	Coarse Aggregate	Fine Aggregate	Water	
E3	5.04	5.66	18.3	73.5	41.3	10.5	3400
E3.5	4.50	6.34	20.5	73.5	39.4	10.5	3840
E4	4.07	7.03	22.8	73.5	37.6	10.5	4290
E4.5	3.74	7.62	24.7	73.5	36.1	10.5	4700
E5	3.40	8.39	27.2	73.5	34.0	10.5	4940
C3	5.63	4.98	16.1	71.8	49.4	10.4	2940
C3.5	5.12	5.48	17.7	71.8	48.1	10.4	3640
C4	4.65	6.13	19.8	71.8	45.8	10.6	4120
C4.5	4.27	6.68	21.6	71.8	44.4	10.6	4610
C5	3.88	7.35	23.8	71.8	42.5	10.6	4950
R'3	5.63	5.06	16.4	65.2	56.0	10.6	3090
R'3.5	5.12	5.56	18.1	65.2	54.5	10.6	3690
R'4	4.65	6.13	19.8	65.2	53.0	10.6	4110
R'4.5	4.27	6.68	21.6	65.2	51.5	10.6	4410
R'5	3.88	7.35	23.8	65.2	49.6	10.6	4950
R3	5.63	5.51	17.8	75.2	42.1	11.5	3150
R5	3.88	7.99	25.9	75.2	35.3	11.5	3620

* 87.5 pounds per bag.

≁ Average of 4 cylinders.

used to keep the sections tightly together. These moulds were of much the same design as those used previously by L. R. Lauer (19). The time required to attain a moisture content below critical saturation under air drying conditions, and the time required to reach temperature equilibrium during the thermal expansion tests were taken into consideration when the diameter was selected.

All concrete mixes were made by hand in a water-tight, galvanized sheet steel mixing boat. The individual batch sizes were small (1.1 cubic feet), and hand mixing in a smooth pan was chosen in preference to the use of a conventional concrete mixer in order to retain a high degree of uniformity in the mortar-coarse aggregate ratio. That is, mortar losses in a conventional mixer must be provided for by "buttering" the mixer according to A.S.T.M. specifications, and this variable was thought better eliminated. The ingredients were batched by weight and thoroughly mixed in a dry state. The mixing water was added and the batch mixed for 3 minutes, allowed to stand 2 minutes, and remixed vigorously for a 2-minute period. The implements which were used are shown in Photograph 1.

Immediately following the mixing, the three test specimens were moulded. The cylindrical moulds were filled vertically in three layers, and each layer was rodded 25 times with a hemispherically tipped, 5/16" diameter steel rod. The surface of each specimen was lightly troweled, and two 3/32" diameter rods were carefully inserted vertically to a depth of 5", one at the center and one at a radius of 1-3/4" along the diameter containing the seam of the mould. This diameter was chosen as the location which would provide the least

PHOTOGRAPH 1. Implements Used in Specimen Manufacture

interference in the continuity of the specimen with regard to the gage points. A length of thin flexible tubing was fitted on each metal rod and the rods were lightly waxed so that when the specimen was removed from the mould the rods could be easily extracted, leaving holes for the insertion of the thermoelement. Photograph 1 shows the finished specimen with flexible tubes still intact and the insertion rods (parts D and E).

The specimens were allowed to stand for about 1/2 hour at which time most of the bleeding had occurred and a cap of warm paraffin wax was poured on the top of each specimen to prevent undue evaporation. The specimens remained in the molds for 24 hours before removal.

Surface Treatment and Curing of Specimens

Upon the removal of the specimens from the molds, they were stored in a fog room maintained at $70^{\circ} \pm 2^{\circ}F$ and between 95 and 100 percent relative humidity, until they were 7 days old.

Preliminary experiments (see Appendix III) indicated the desirability of filling the surface voids along the "SR-4" strain gage lines to provide a continuous bonding surface. Suitable gage lines contained in two axial planes mutually at right angles were selected on the surface of each specimen. The specimens were scraped free of surface deposits along these lines, thoroughly rinsed with water, and surface dried to a damp condition. A 1:1 cement-sand mortar of putty-like consistency was worked into the surface voids. It was always possible to select the location of the gage lines such that no void larger than about 1/16 inch in diameter needed to be filled, and there were

generally not more than two or rarely three such surface voids on an individual 6" gage line. The mortar was made with the same cement as had been used for the specimen and with sand passing a No. 50 sieve.

All specimens were subsequently returned to the fog-room until they were a total of 28 days old.

Following the fog-room curing, all specimens were placed on racks in a "constant" temperature and humidity room for 41 days of accelerated air drying, except that types R3 and R5 were dried for 80 and 73 days respectively. The temperature was about 78°F and the relative humidity was 34 ±10 percent. The apparatus was not capable of producing entirely constant conditions. The drying conditions are shown in Figure 2.

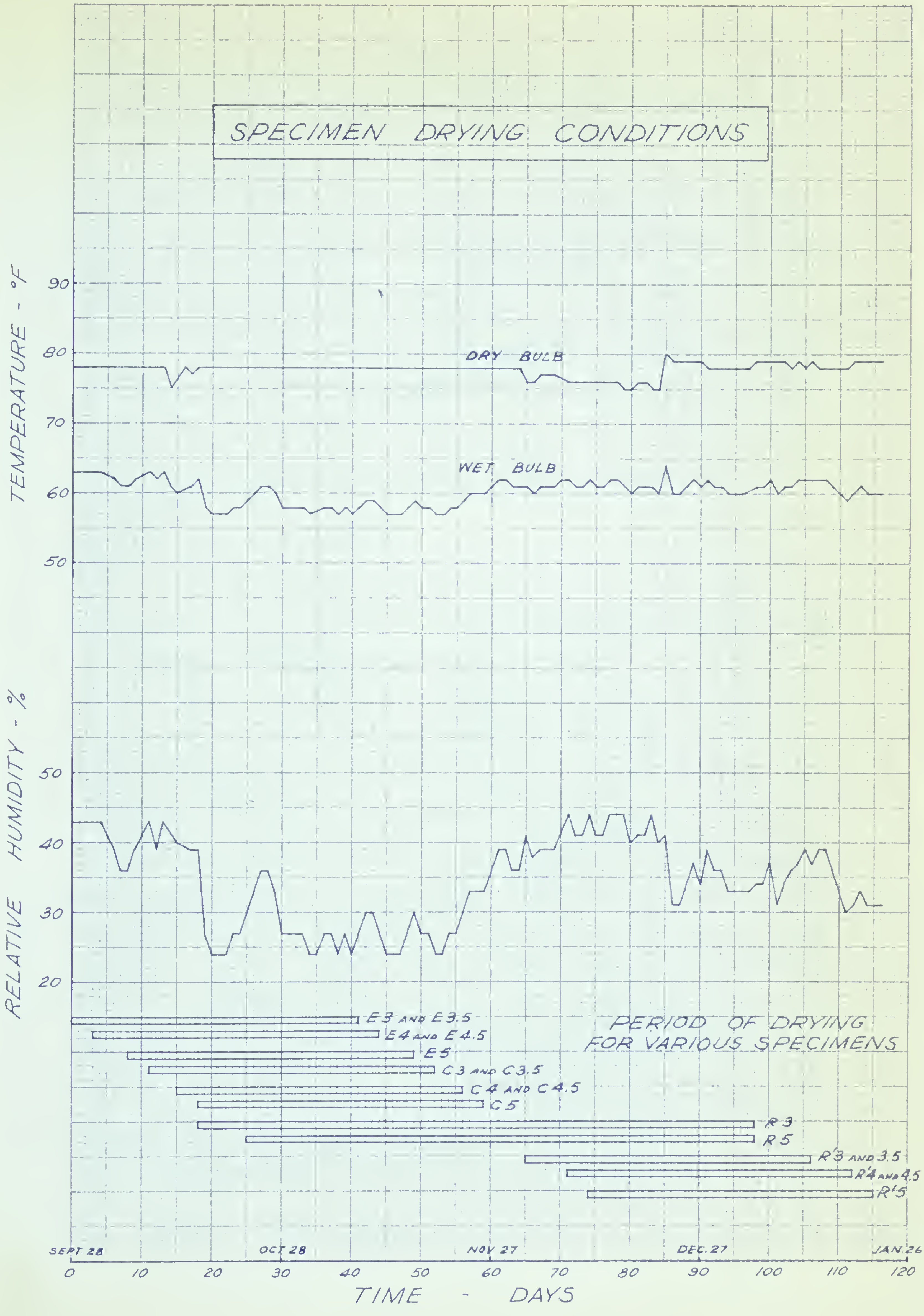

SPECIMEN DRYING CONDITIONS
TEMPERATURE - °F
90
80
70
60
50
DRY BULB
WET BULB
RELATIVE HUMIDITY - %
50
40
30
20
E3 AND E3.5
E4 AND E4.5
E5
C3 AND C3.5
C4 AND C4.5
C5
R3
R5
R'3 AND 3.5
R'4 AND 4.5
R'5
PERIOD OF DRYING FOR VARIOUS SPECIMENS
SEPT. 28
OCT 28
NOV 27
DEC. 27
JAN. 26
0
10
20
30
40
50
60
70
80
90
100
110
120
TIME - DAYS

FIGURE 2

CHAPTER IV

INSTRUMENTATION AND TEST PROCEDURES

In general, length measurements were obtained for each specimen at several equilibrium temperatures between -40°F and +100°F by means of "SR-4" electrical resistance strain gages and a demountable mechanical ("Demec") strain gage. The apparatus used as the cooling and heating mechanism was a converted refrigeration unit. Specimen temperatures were read directly from and recorded by a "Brown Electronik" potentiometer and recorder of -50°F to +100°F range.

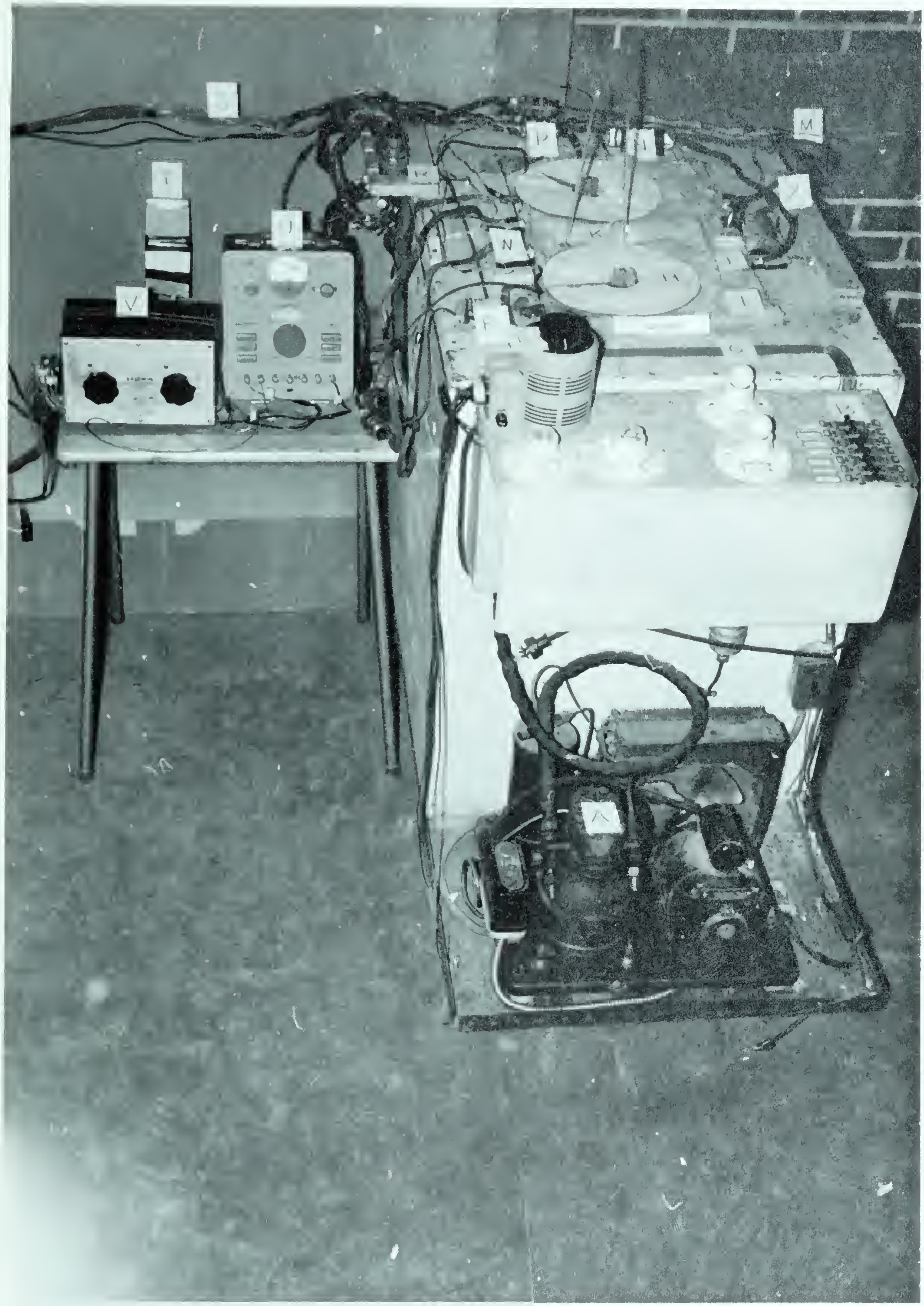
Temperature Control Cabinet

Photograph 2 is a general view of the temperature control cabinet and Photograph 3 shows the cabinet in more detail.

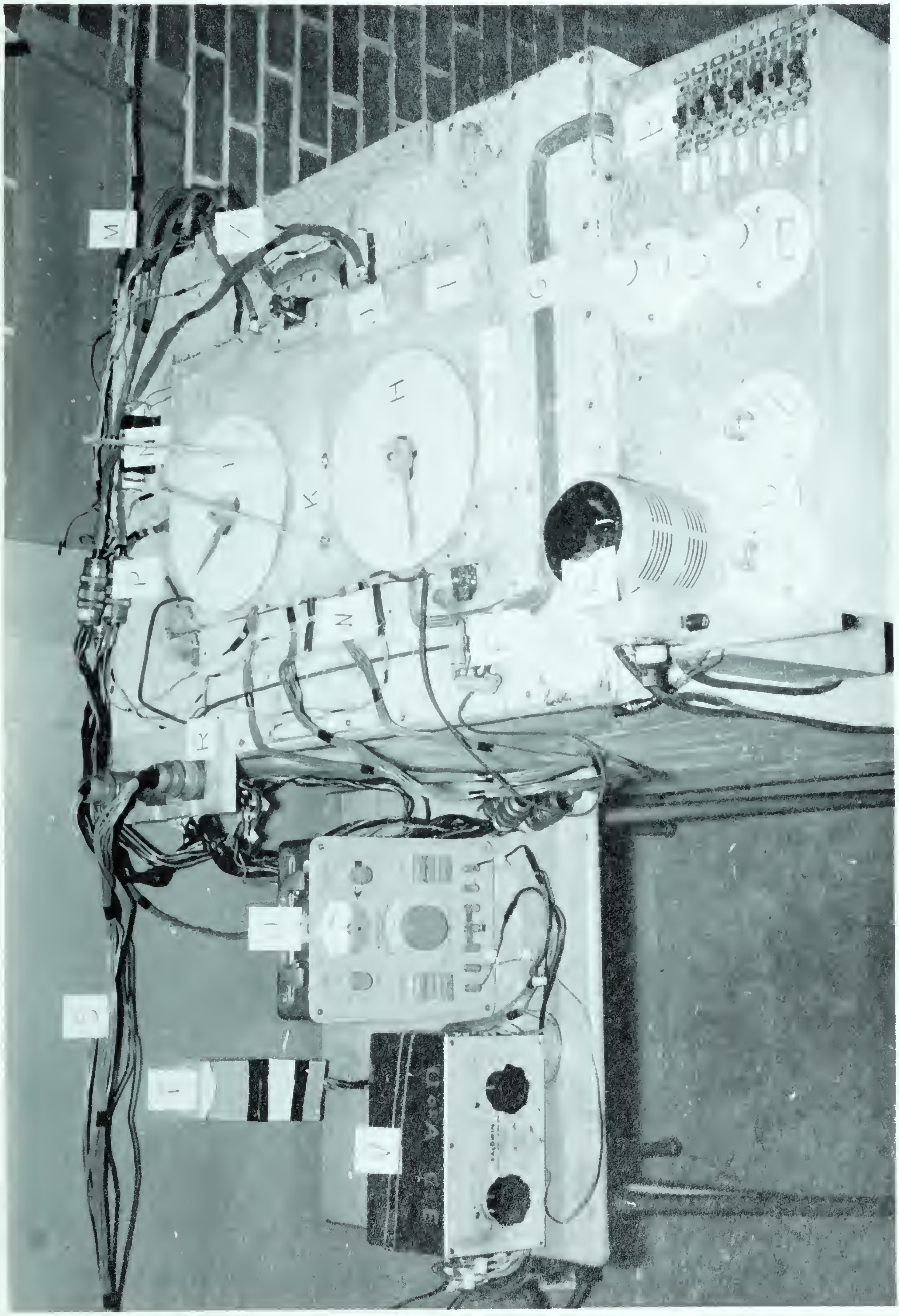
The interior elements of the cabinet are shown in Photograph 4. The heating unit, Part 1, was fabricated with two separate elements such that the heat output could be varied by switching one element, two in series, or two in parallel. The fan, Part 2, was introduced to provide positive circulation within the cabinet. An expanded steel mesh grid was mounted on the supports, Part 3, to form a base for the specimens (see Photograph 6).

The make up and control of the cabinet can be best understood by referring to the notation of parts on Photograph 2 and particularly Photograph 3 with reference to the following descriptions:

A - Refrigeration mechanism consisting of a motor, compressor, and heat exchanger.



PHOTOGRAPH 2. Temperature Control Cabinet - General View



PHOTOGRAPH 3. Temperature Control Cabinet - Detail View

PHOTOGRAPH 4. Interior of Temperature Control Cabinet

B - Switch bank in control of:

1. Refrigeration mechanism .
2. Interior heating elements.
3. On - Off indicator lights.

C - Indicator lights which could be switched on with, or in place of the refrigeration unit and the heating element.

D - Circuit fuses, one for the hot circuit and one for the cold circuit.

E - "Variac Powerstat" for fine control of the heat output of the heating unit.

F - Capacitors to prevent arcing of the thermostat contacts.

G - Lead wires to thermostats and heater.

H - Hot thermostat and fabricated dial.

I - Fibreglass insulation over plywood lid.

J - Flap in insulation under which a narrow double pane window was fitted in the lid of the box. A total immersion thermometer was suspended about 4" below the window.

K - Partial immersion thermometers.

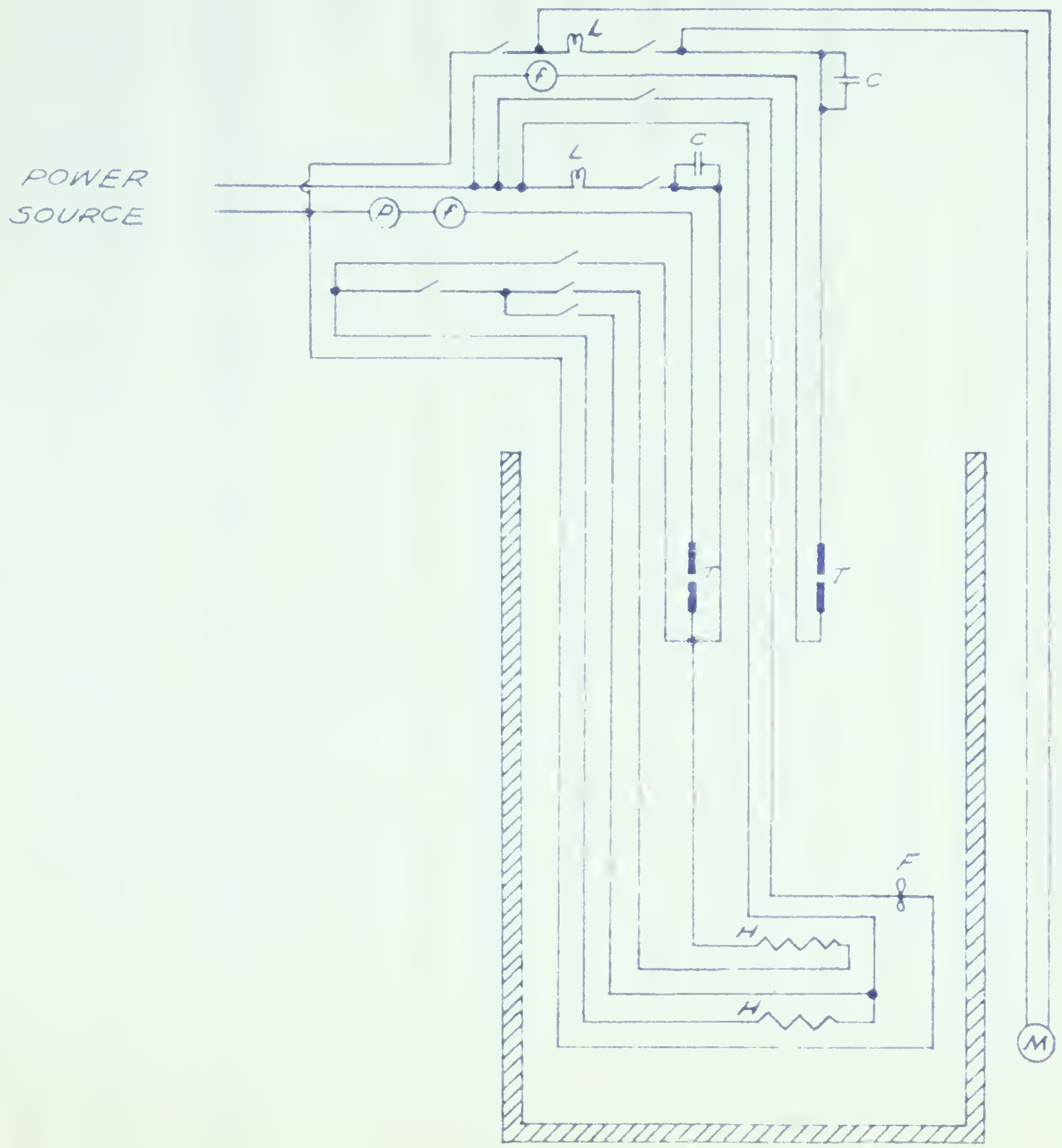
L - Cold thermostat and fabricated dial.

M - Thermocouple leads to the Brown Potentiometer.

N - Dry cells for the operation of a small non-heat producing light within the box to facilitate reading the total immersion thermometer.

The remaining parts are described later in connection with the final assembly and "SR-4" instrumentation.

The schematic circuit diagram for the unit is shown in Figure 3.



KEY

C CONDENSER
f FUSE
F FAN
H HEATING ELEMENT
L INDICATOR LIGHT
M COMPRESSOR MOTOR
P "POWERSTAT"
T THERMOSWITCH

SCHEMATIC CIRCUIT DIAGRAM
OF
TEMPERATURE CONTROL CABINET

FIGURE 3

The operation of the temperature control apparatus was simple. If it was desired to increase the temperature, for example, the refrigeration unit was switched out and the heating elements switched in. When the desired temperature was reached, the cold thermostat was adjusted to cut in by observing the cold indicator light, the heating element switched out, and the refrigeration unit switched in. Several hours were usually required for the specimens to reach approximate equilibrium with the cabinet temperature. Unfortunately, the thermostatic controls were not sufficiently sensitive to temperature change, and fine control of the temperature to give constant conditions over an extended period could only be achieved manually. During this stage the refrigeration unit was allowed to run continuously and small quantities of heat were introduced with the assistance of the "Variac Powerstat". An alternative method which was often used, involved having both the heating and refrigeration units switched out and manually operating the switch for the refrigeration unit to maintain temperature conditions. In all instances, a small rise or drop in the cabinet temperature ($\pm 0.2^{\circ}F$) could be observed on either the thermometers or the recording potentiometer or both, and the necessary adjustments made. About one hour of such constant temperature condiions was required for the specimens to reach equilibrium with the cabinet.

Attachment of "SR-4" Strain Gages, "Demec" Gage Points, and Insulation

The preparation of the specimens for testing was initiated six days prior to the scheduled thermal expansion test. The preparation

operations were performed, as much as possible, in the constant humidity room to avoid undue interruption of the drying process. The procedures which were followed were based upon experience gained during preliminary tests (see Appendix III).

Specimens were ground with a powered belt sander along the gage lines mentioned in Chapter III until all loose surface material was removed and the parent concrete cleanly exposed. The surface of each specimen was blown clean with the aid of a high pressure air jet and washed thoroughly with acetone. A mixture of "C.I.L. Household Cement" thinned in acetone was rubbed into the surface to fill any small surface pores. This was allowed to dry for 24 hours and the "Type A-9 SR-4" strain gages were cemented to the surface using a generous quantity of "C.I.L. Household Cement". The gage was held in place by means of a strip of sponge rubber on a wood backing until the cement became tacky (1 or 2 minutes). This procedure is in compliance with the strain gage manufacturer's recommendations and similar to procedures suggested by several authorities (20, 21, 22, 23).

The "Demec" gage points were mounted 24 hours after the "SR-4" strain gages. The gage points consisted of shallow, cylindrical, metal discs with a No. 60 drill hole in the center and passing part way through the disc. These were provided by the manufacturer along with the gage and are described in detail by Base (24, 25), together with the method of attaching. The gage "discs" were mounted by means of sealing wax and a hot soldering iron. The correct gage distance was obtained by heating one of the discs, after it was mounted, and slipping it along the surface of the concrete to fit the setting-out

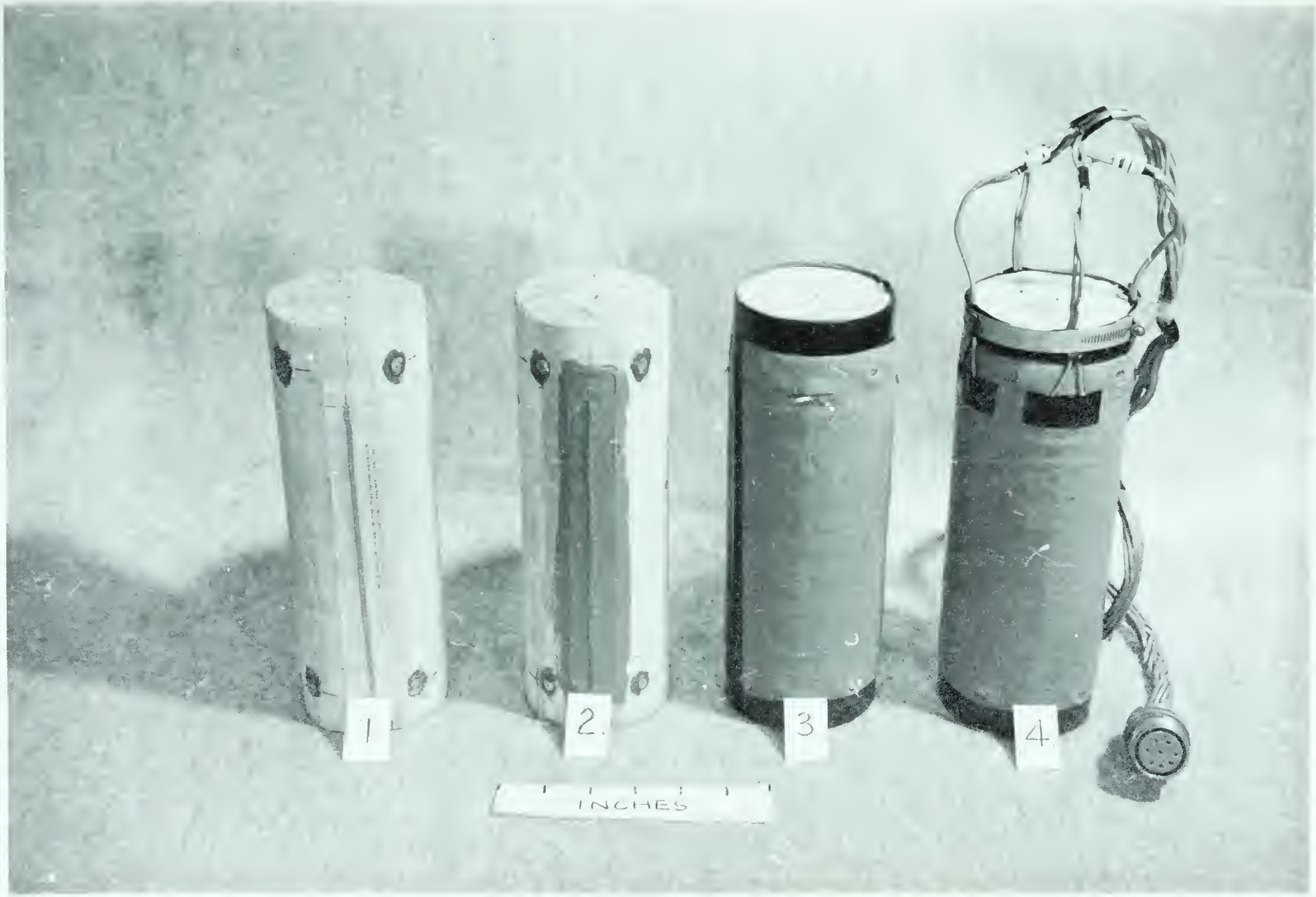
gage bar. The discs were always checked for proper bond.

The surfaces and edges of the "SR-4" strain gages were next given a thorough coat of liquid neoprene which was allowed to set for 24 hours. The specimens were wrapped with two layers of commercially available felt cloth to provide a layer of felt insulation about 1/8" thick. This insulation was provided to serve two functions; namely, to produce a damping effect on the influence of temperature fluctuations within the cabinet upon the specimens, and to prevent undue temperature change of the specimens when removed for "Demec" gage readings. Holes were cut in the insulation to expose the "Demec" gage discs. The "SR-4" gage lead wires were brought through slits in the felt.

The "SR-4" strain gage lead wires were soldered to 16 gage solid copper wire leads having "Flamenol" insulation. The connection was protected by means of a strip of plastic electrician's tape. The lead wires were firmly attached to the specimen with 3" diameter hose clamps to prevent accidental damage to the strain gages. The free ends of the lead wires were soldered to a tin-plated, eight point, female "Cannon" connector.

The steel specimens were prepared in much the same manner as were the concrete specimens, except that the "Demec" gage points were drilled into the sample, and a support was provided such that the specimens could be stood on end.

Specimens in the various stages of preparation are shown in Photograph 5.



PHOTOGRAPH 5. Specimens in Various Stages of Preparation

Circuit and Function of "SR-4" Strain Gages

The use of "SR-4" electrical resistance strain gages in the measurement of unit length changes due to temperature is somewhat more involved than the usual application in which strains due to applied force are measured. In the usual application a "dummy" gage is mounted on a sample of the same material as that which is being loaded, in order to compensate for length changes in the loaded specimen due to temperature changes, as well as to compensate for changes in the resistance of the "active" gage due to temperature alone. When the active gage is utilized to measure unit length changes in a body which are due to temperature changes alone, then the function of the dummy gage must be to compensate only for changes in resistance of the wire in the active gage itself, due to temperature change. This form of compensation could be achieved by the use of a dummy gage mounted upon a material of zero thermal coefficient and subjected to the same temperature conditions as the active gage. For the same reason the lead wires to both the active and dummy gages would need to be at a common temperature.

No material with a zero thermal coefficient between -40°F and +100°F is known to the author. Another solution to the problem is evident in the use of a material of known thermal coefficient. The active gage then registers only the difference in unit length change due to temperature change for the materials to which the active and dummy gages are attached. If the length-temperature relationship of the material to which the dummy gage is attached is known accurately, then it is possible to obtain the length-temperature relationship for

the material to which the active gage is attached by simple algebraic summation. It was this method which was used in the tests.

An aluminum specimen (Sample GY) of known thermal expansion characteristics was obtained from the United States National Bureau of Standards at Washington. This sample was used as the dummy throughout the tests. Thermal expansion data as determined by the Bureau for this sample follow:

Temperature ^{o}F	Linear Thermal Expansion %
-50.0	-0.141
-20.0	-0.107
+10.0	-0.072
+40.0	-0.036
+70.0	0.000
+100.0	+0.037
+130.0	+0.075

The sample was 8 inches long and 1/2 by 5/16 inch in cross section.

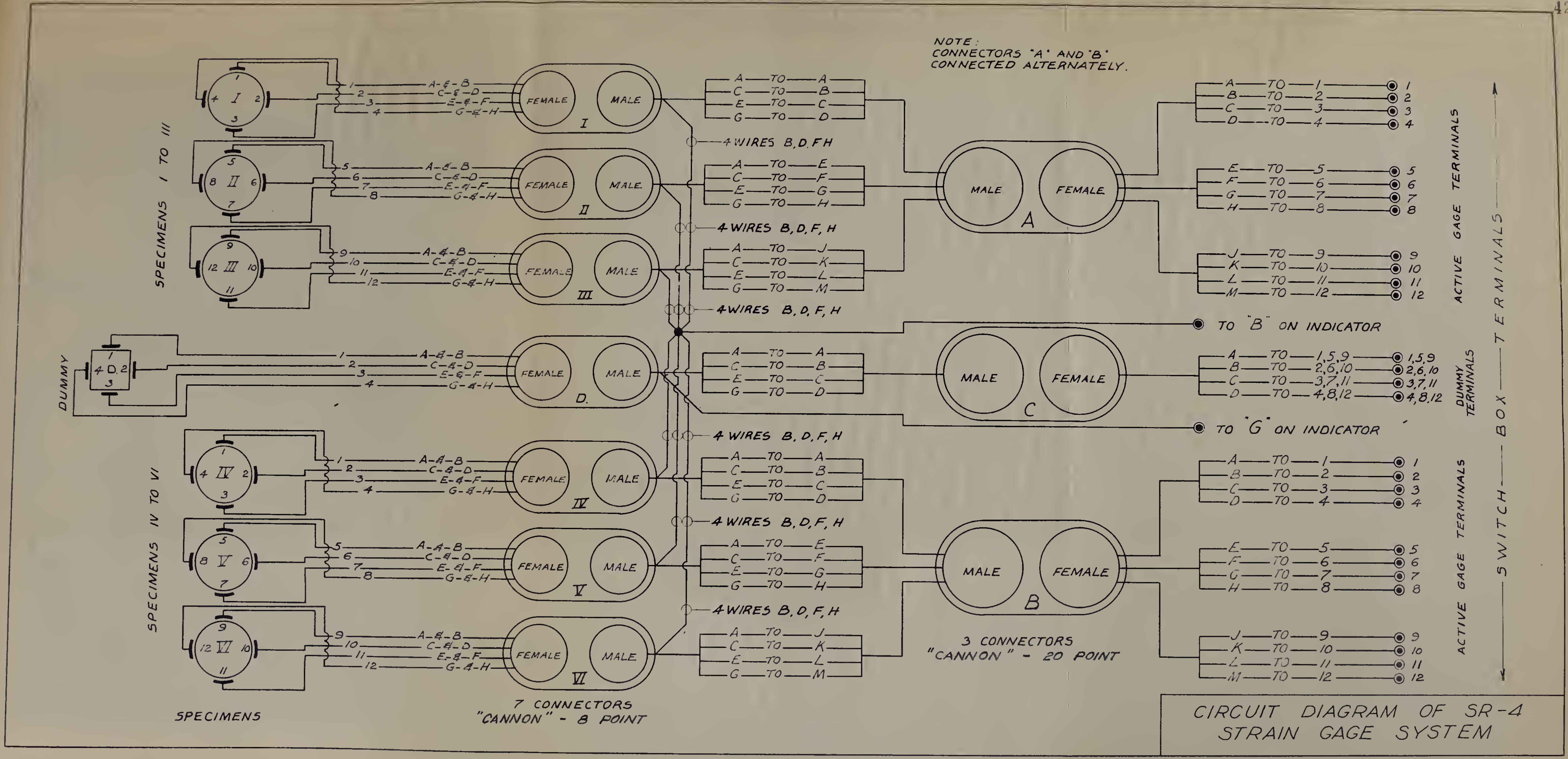
As described previously, four six inch "SR-4" strain gages were mounted on each specimen. In order to provide for individual compensation and maintain a consistent measurement system for each active gage, four dummy gages were fixed to the aluminum bar. The bar was insulated and mounted on a support so that it could be stood on end. The circuit was arranged such that the four active gages for each specimen were compensated by four dummy gages and by means of a

switch box and "Cannon" connectors six specimens could be tested. The circuit diagram for the six specimen system is shown schematically in Figure 4.

In order to measure any drift in instrument zero for the transistor-type strain indicator, so that appropriate correlations could be made, four "SR-4" strain gages were mounted on a steel bar. The bar was insulated with "Vermiculite" to prevent the adverse effects of local temperature change on the gages. Each set of two opposite gages were connected to the indicator through the switch box such that one was active and the other dummy. A reading could then be obtained, the active and dummy leads reversed at the indicator and a second reading obtained. The mean of the two readings thus obtained would give an instrument zero reference at the start of each test run and periodic checks could be made to determine any drift in the instrument.

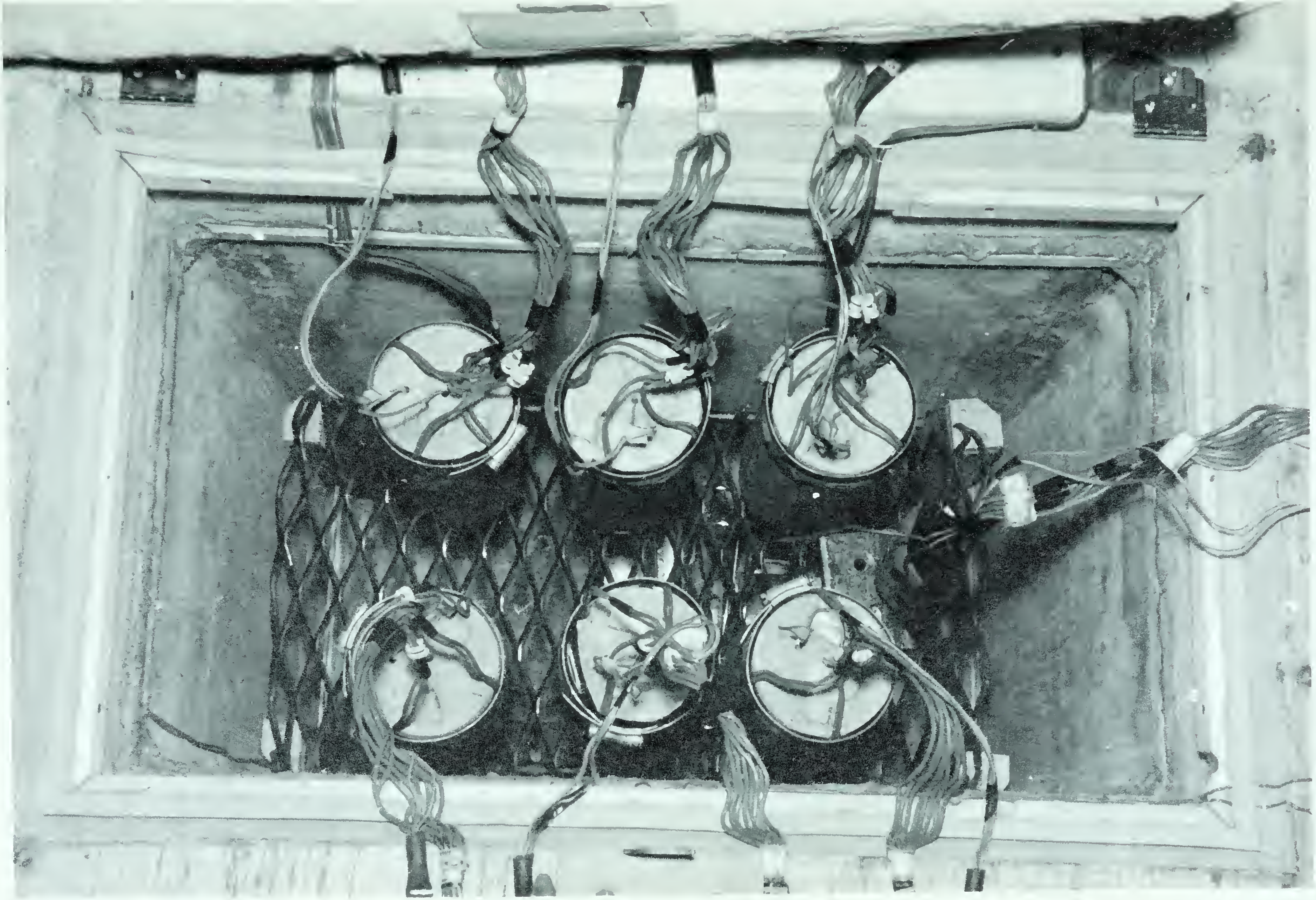
Assembly for Test

Six specimens representing two separate concrete types together with the aluminum comparator were arranged within the temperature control cabinet as shown in Photograph 6. Iron-constantan thermocouples having a thin neoprene coating were inserted into the holes provided in each specimen. Two thermocouples were installed under the insulation of the aluminum comparator and two more were arranged to read cabinet air temperature. The copper wire leads to each specimen and the aluminum comparator were adjusted to have the same lengths. The female connector attached to the leads from each



CIRCUIT DIAGRAM OF SR-4 STRAIN GAGE SYSTEM

FIGURE 4



PHOTOGRAPH 6. Specimens Rigged for Testing

specimen was brought into contact with the appropriate male connector at the exterior of the cabinet and the lid was closed. The appropriate connection was made from the specimens to the "SR-4 Strain Indicator" through connector A or B (see Figure 4).

The apparatus in ready to operate assembly has been shown in Photograph 3. The parts dealing with the final assembly and "SR-4" instrumentation are as follows:

P - Eight Point "Cannon" connectors.

R - Twenty Point "Cannon" connectors.

S - Lead wires to switch box.

T - Instrument zero drift measuring gages in housing.

U - "Baldwin SR-4 Strain Indicator, Type N".

V - "Baldwin 20 gage Switch Unit".

W and X - Lead wires from Specimens.

Test Procedure

On the evening of the 41st day of air drying (except for types R3 and R5) six specimens and the aluminum comparator were assembled in the temperature control cabinet, and the refrigeration unit was set to run continuously. The circulation fan and the recording potentiometer were put into operation. The cabinet reached its minimum temperature about -37°F in about 14 hours. The specimens had reached thermal equilibrium with the cabinet at least one hour earlier.

After an initial check on instrument zero, the first set of readings were taken. The "SR-4" strain gage readings (four for each specimen) were taken for the first set of three specimens, and

temperatures were read on the "Brown Recorder" almost simultaneously (±2 minutes). The smallest division on the "SR-4" strain indicator was 10 micro-inches per inch and readings were estimated to the micro-inch per inch. The smallest division on the "Brown Recorder" temperature scale was 0.5°F and temperatures were estimated to 0.1°F. Immediately after the readings had been taken for the first three specimens, the 20 point connection was changed so that the readings for the next three specimens could be taken. After all of the readings were completed, instrument zero was again checked.

The next step involved taking the "Demec" gage readings (four for each specimen). Temperature readings were taken for each specimen prior to its removal from the cabinet. The specimen was lifted out of the cabinet, the lid of the cabinet closed, and the specimen set horizontally on a rest at the edge of the top of the cabinet. Readings for the four gage points were taken in fairly rapid succession by rotating the specimen from one gage point to the next and always reading the Demec gage in a horizontal position. About two minutes were usually required to read each specimen. The smallest division on the dial indicator represented a little less than five micro-inches per inch and readings were estimated to the micro-inch per inch. Each specimen was returned to the cabinet immediately after reading and the next specimen removed. The procedure was repeated until readings for all specimens had been obtained.

In some of the tests an initial set of readings, both "SR-4" and "Demec", were taken at room temperature prior to the readings just described in order to obtain a measure of the "permanent set" (8, 12).

A similar procedure was followed to obtain readings at intervals of 25°F to 30°F up to 97°F. In all cases temperature equilibrium between the specimens and cabinet air had been obtained and held for about 30 minutes prior to reading. Equilibrium was considered to exist when the cabinet and specimens were within 0.2°F of each other.

About six hours were required to change from equilibrium conditions at one temperature to another. Two readings were usually taken each day for three days to complete a given test. This procedure was sufficient to describe a "slow" test (8).

The procedure described was followed for all test runs, the only exception being the first test which was on concrete types E3 and E3.5. For these specimens it was necessary to obtain the "SR-4" strain gage readings and "Demec" gage readings separately and during separate test runs. The reason for this procedure was that an adequate system of assembling the specimens within the cabinet had not been devised. If the "SR-4" strain gage lead wires were to be kept attached to the specimens, all of the specimens had to be removed before taking any one set of "Demec" gage readings. The specimens were not adequately insulated for such procedure.

CHAPTER V

TEST RESULTS

The results of the thermal expansion tests are shown in Tables 8 to 25. In view of the large volume of the original test data and the number of calculations necessary to reduce the original data to obtain the final information desired, only the reduced data have been included here.

The data presented for each specimen have been reduced from the mean of four readings (only two readings for R3, R5, and the No. 8 steel bars) on individual "SR-4" strain gages or "Demec" gage points and two thermocouple readings. The temperatures have been corrected according to the calibration chart presented in Appendix III and the unit length change reductions have been made with reference to a datum at 70°F.

Sample calculations describing the process of reducing the data are given in Appendix I. The original data and reductions are on file with the Department of Civil Engineering, University of Alberta.

Figures 5 to 21 accompanying the reduced data, show the thermal expansion characteristics of each concrete type as indicated by the mean of the readings for the three specimens. The reduced readings for each specimen were originally plotted separately but it was found that the points for the three curves representing each concrete type were generally so close together that separate curves could not be drawn with any degree of clarity. Furthermore, the main purpose of testing three specimens of a kind was to obtain a good average for

each concrete type.

The "best fit" curve for each concrete type was obtained by eye. Much more personal error was involved in obtaining the "Demec" strain gage readings than in obtaining the "SR-4" strain gage readings. Furthermore, the primary purpose of the "Demec" strain gage readings was to provide a continuous check on the "SR-4" strain gage readings. These factors were considered in selecting the "best fit" curves by placing more emphasis on the points representing the "SR-4" strain gage readings.

Similar reasoning was used in obtaining the thermal expansion characteristics shown in Figure 22 for the No. 8 concrete reinforcing bar.

Table 8 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE E3

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	-22.8	-513	-22.6	-549	-22.7	-512	-22.7	-525
5	+ 7.7	-364	+ 9.0	-397	+ 9.4	-374	- 8.7	-378
20	+32.3	-201	+34.4	-223	+35.4	-216	+34.0	-213
25	+67.2	+ 24	+69.5	+ 24	+70.0	+ 20	+68.9	+ 23
30	+96.1	+200	+96.2	+208	+96.5	+201	+96.3	+203
REDUCED DEMEC STRAIN GAGE READINGS								
0	-33.8	-551	-33.7	-549	-33.8	-542	-33.8	-547
20	-21.9	-501	-21.9	-508	-21.9	-490	-21.9	-450
33	+ 4.0	-377	+ 4.0	-369	+ 4.1	-349	+ 4.0	-365
37	+34.4	-221	+35.1	-219	+36.3	-194	+35.3	-211
43	+73.9	+ 25	+72.4	+ 15	+73.9	+ 23	+73.4	+ 21
63	+96.5	+165	+96.5	+181	+96.5	+187	+96.5	+178

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE E 3

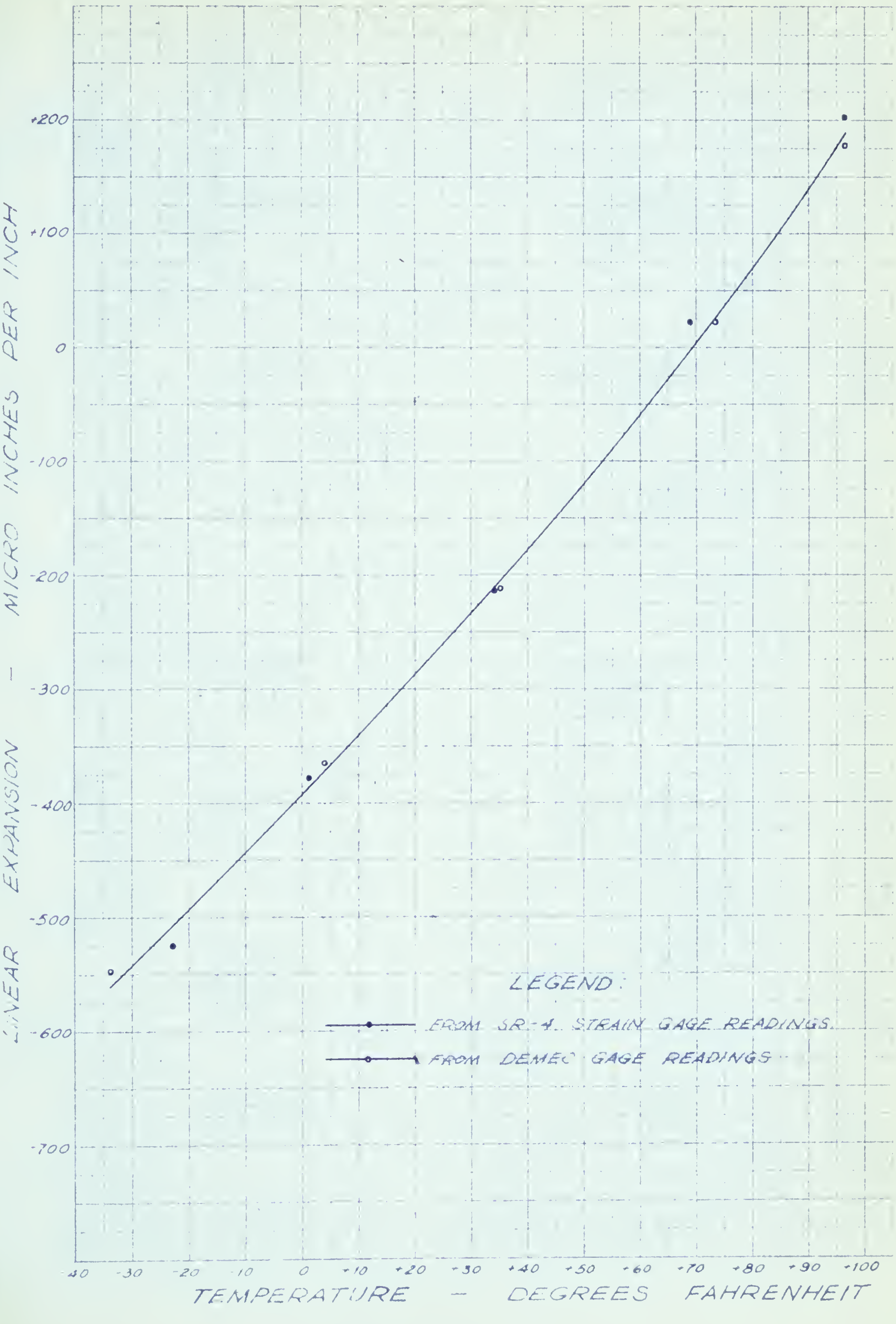


FIGURE 5

Table 9

REDUCED THERMAL EXPANSION DATA

CONCRETE TYPE E3.5

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	-21.8	-504	-21.5	-519	-21.3	-515	-21.5	-513
5	+ 8.7	-371	+ 9.2	-370	+ 9.7	-371	+ 9.2	-371
20	+33.7	-214	+34.7	-207	+35.6	-207	+34.7	-209
25	+69.7	- 30	+71.8	+ 38	+73.0	+ 39	+71.5	+ 16
30	+96.4	+196	+96.8	+203	+96.9	+204	+96.7	+201
REDUCED DEMEC STRAIN GAGE READINGS								
0	-33.7	-550	-33.7	-562	-33.5	-553	-33.6	-555
20	-21.3	-506	-21.3	-496	-21.3	-498	-21.3	-500
33	+ 4.0	-367	+ 4.0	-364	+ 4.4	-362	+ 4.1	-364
37	+34.6	-208	+34.8	-207	+35.5	-201	+35.0	-205
43	+73.9	+ 23	+73.9	+ 23	+73.9	+ 23	+73.9	+ 23
63	+96.3	+186	+96.6	+183	+96.7	+193	+96.5	+187

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE E 3.5

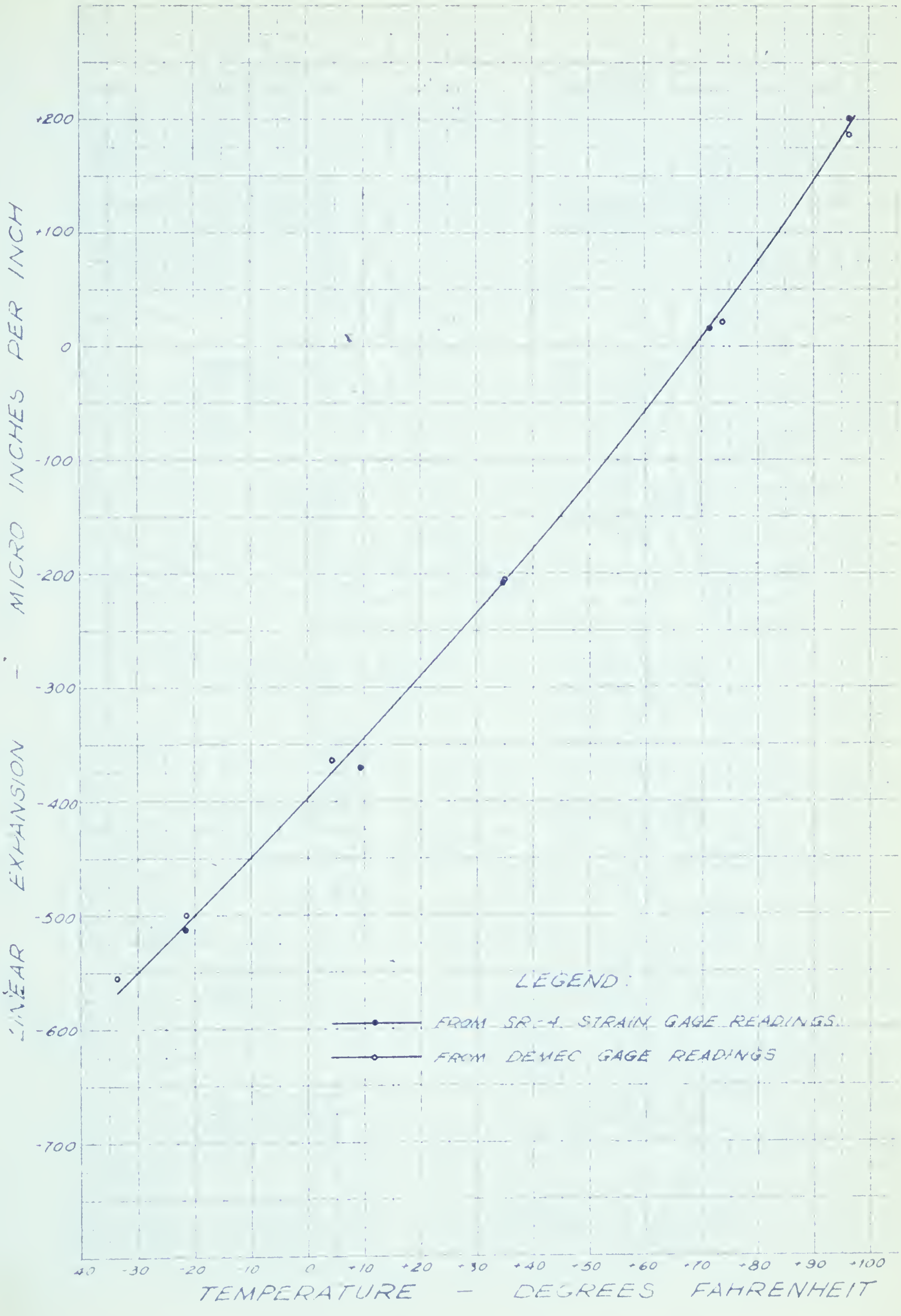


FIGURE 6

Table 10 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE E4

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	-36.7	-593	-36.7	-616	-36.7	-616	-36.7	-608
5	+ 0.1	-411	- 1.0	-427	- 1.0	-428	- 0.6	-422
17	+17.2	-333	+17.2	-332	+16.9	-329	+17.1	-331
23	+53.1	-117	+53.2	-121	+52.7	-111	+53.0	-116
44	+72.2	+ 15	+72.2	+ 16	+72.2	+ 15	+72.2	+ 15
51	+97.6	+216	+97.6	+223	+97.6	+212	+97.6	+217
REDUCED DEMEC STRAIN GAGE READINGS								
0	-34.3	-589	-34.3	-562	-34.4	-536	-34.3	-562
5	+ 0.3	-391	- 0.7	-399	- 0.7	-413	- 0.4	-401
17	+18.3	-307	+18.0	-306	+17.7	-316	+18.0	-310
23	+53.2	-105	+53.2	- 99	+52.7	-104	+53.0	-103
44	+72.2	+ 14	+72.2	+ 13	+72.2	+ 14	+72.2	+ 14
51	+97.9	+186	+97.9	+201	+97.9	+203	+97.9	+197

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE E4

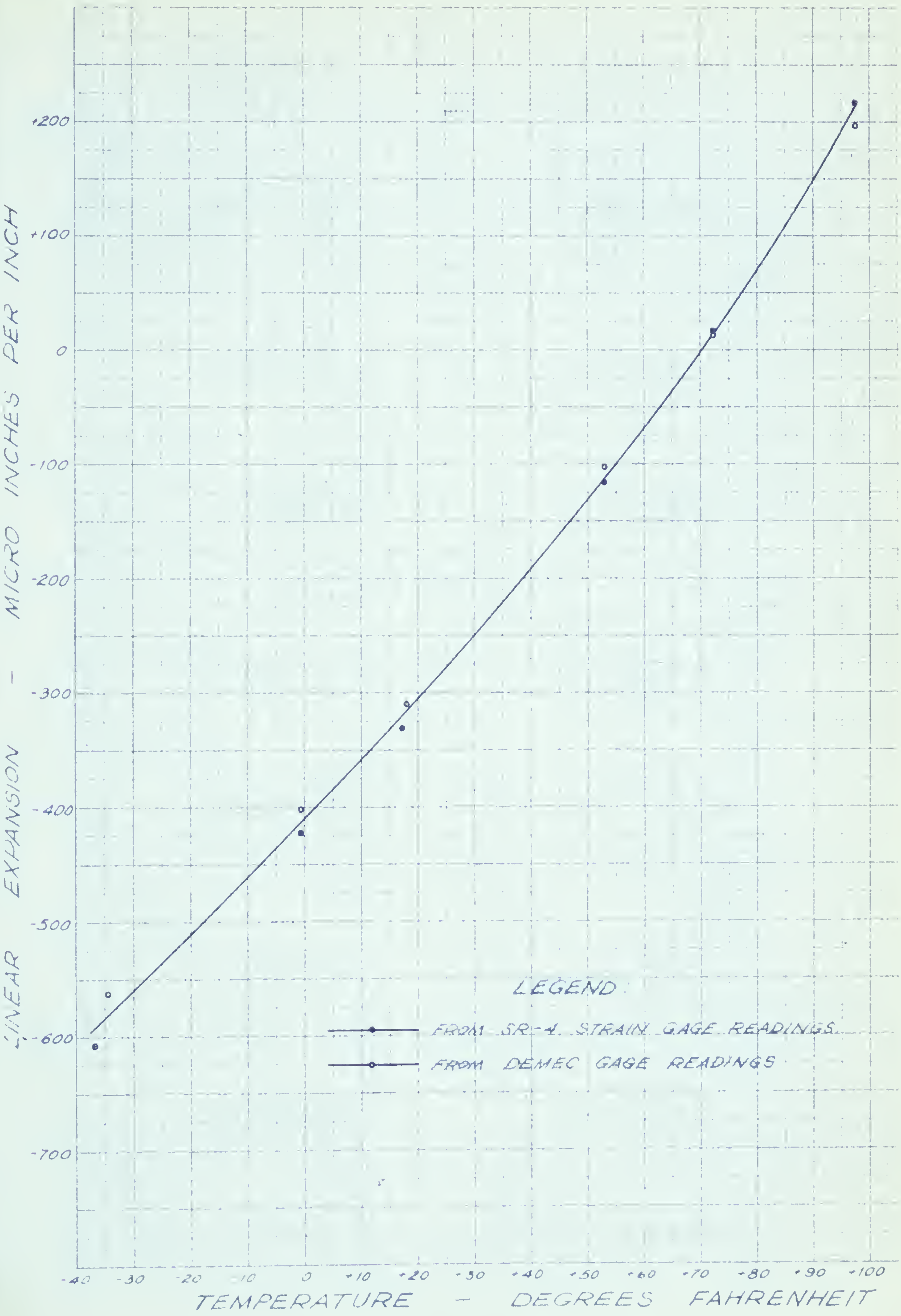


FIGURE 7

Table 11 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE E4.5

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	- 36.7	- 587	- 36.7	- 591	- 36.7	- 591	- 36.7	- 590
5	+ 0.3	- 428	- 0.1	- 427	- 2.6	- 421	- 0.8	- 425
17	+ 19.3	- 345	+ 19.0	- 342	+ 17.0	- 335	+ 18.4	- 340
23	+ 53.5	- 114	+ 53.2	- 112	+ 52.5	- 116	+ 53.1	- 114
44	+ 72.2	+ 16	+ 72.2	+ 16	+ 72.2	+ 16	+ 72.2	+ 16
51	+ 97.7	+ 220	+ 97.8	+ 216	+ 97.8	+ 220	+ 97.8	+ 219
REDUCED DEMEC STRAIN GAGE READINGS								
0	- 34.1	- 572	- 34.3	- 572	- 34.3	- 578	- 34.2	- 574
5	+ 0.3	- 402	- 0.1	- 407	- 2.6	- 419	- 0.8	- 409
17	+ 19.2	- 305	+ 19.1	- 312	+ 17.2	- 319	+ 18.5	- 312
23	+ 53.1	- 103	+ 53.1	- 105	+ 52.5	- 109	+ 52.9	- 106
44	+ 72.3	+ 14	+ 72.3	+ 14	+ 72.3	+ 15	+ 72.3	+ 14
51	+ 97.9	+ 196	+ 97.9	+ 195	+ 97.9	+ 197	+ 97.9	+ 196

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE E 4.5

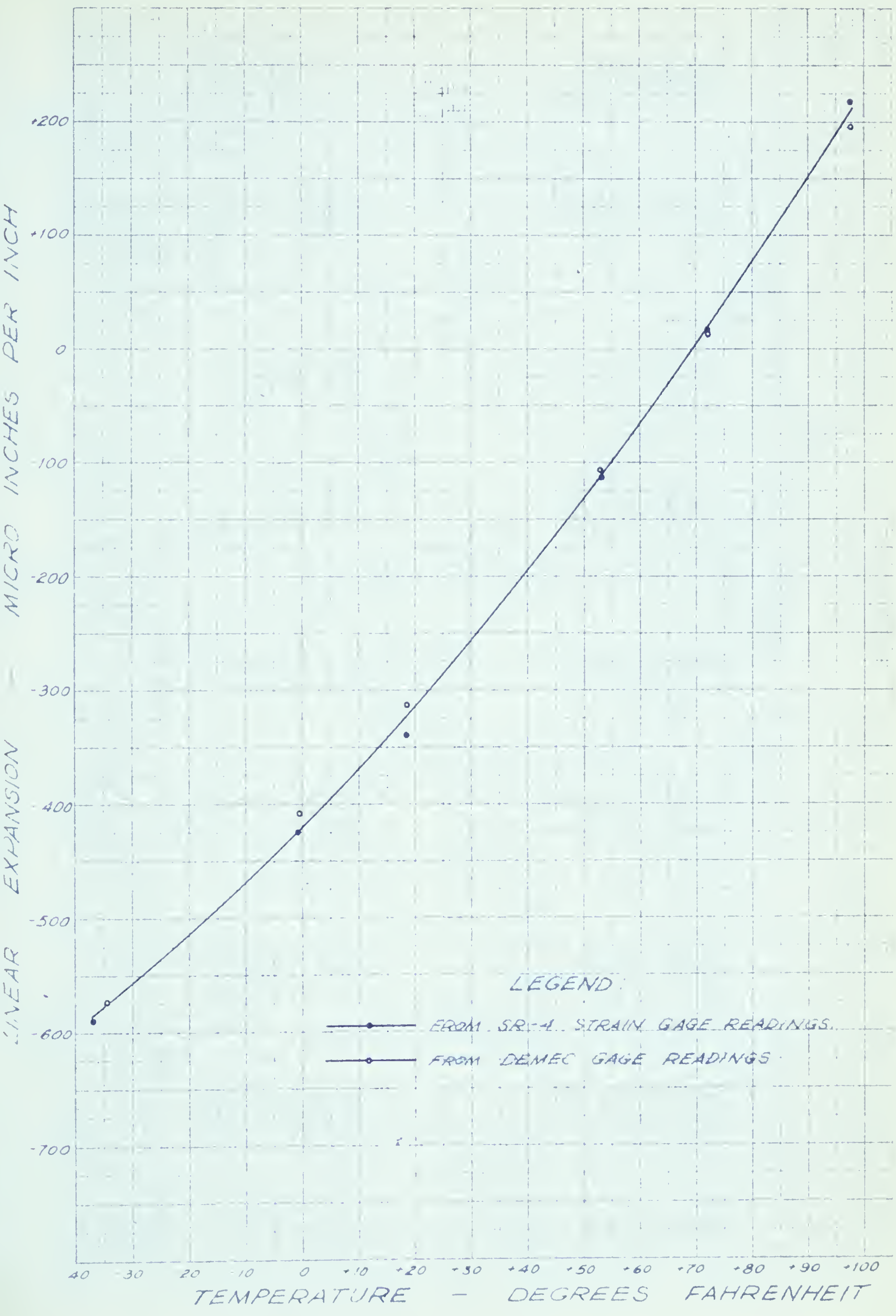


FIGURE 8

Table 12 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE E5

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	+69.7	- 36	+69.7	- 34	+69.7	- 34	+69.7	- 35
14	-38.3	-615	-38.2	-610	-38.2	-594	-38.2	-606
19	- 6.5	-443	- 6.4	-439	- 5.5	-432	- 6.1	-438
38	+21.8	-310	+22.2	-302	+23.3	-294	+22.4	-301
43	+37.5	-219	+37.5	-218	+37.5	-217	+37.5	-218
63	+67.7	- 12	+67.7	- 10	+67.7	- 8	+67.7	- 10
69	+94.9	+208	+94.8	+206	+95.4	+198	+95.0	+204
REDUCED DEMEC STRAIN GAGE READINGS								
0	+69.8	- 16	+69.8	- 25	+69.8	- 30	+69.8	- 24
14	-38.1	-606	-38.1	-607	-38.2	-605	-38.1	-606
19	- 6.5	-490	- 6.4	-437	- 5.5	-427	- 6.1	-451
38	+22.5	-300	+22.5	-318	+22.5	-323	+22.5	-314
43	+37.8	-213	+37.8	-213	+37.8	-210	+37.8	-212
63	+67.8	- 16	+67.8	- 16	+67.8	- 17	+67.8	- 16
69	+95.0	+173	+94.9	+183	+95.4	+188	+95.1	+181

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE E5

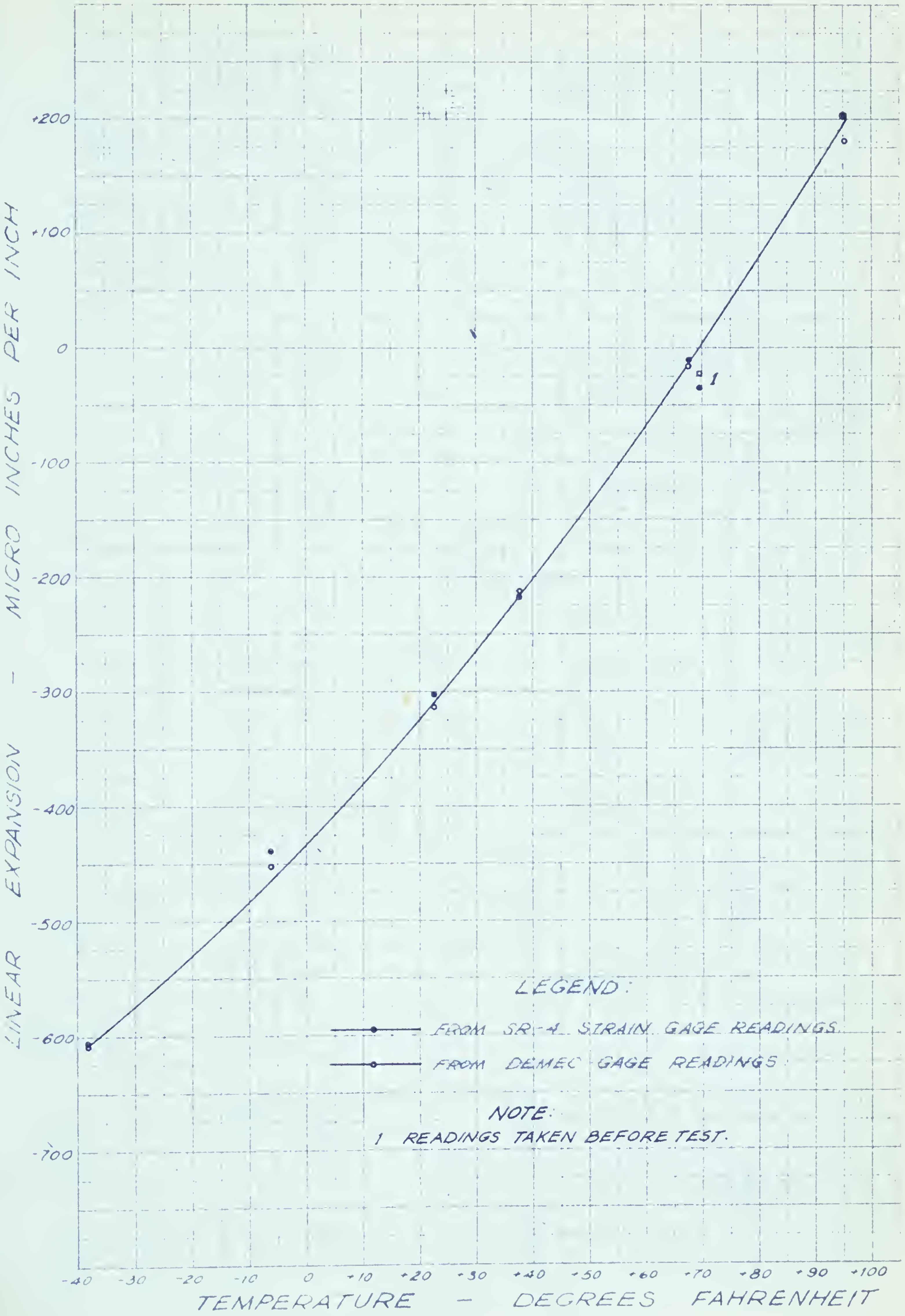


FIGURE 9

Table 13 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE C3

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	-35.5	-519	-35.5	-544	-35.6	-522	-35.5	-529
5	- 1.8	-385	- 1.8	-402	- 1.8	-386	- 1.8	-391
25	+24.4	-238	+24.7	-250	+24.9	-240	+24.7	-243
30	+46.5	-124	+46.5	-133	+47.0	-132	+46.7	-130
51	+95.8	+154	+95.7	+154	+95.7	+145	+95.7	+151
72	+73.4	+ 20	+73.4	+ 21	+73.4	+ 21	+73.4	+ 21
REDUCED DEMEC STRAIN GAGE READINGS								
0	-35.7	-496	-35.6	-514	-35.6	-510	-35.6	-507
5	- 1.4	-342	- 1.4	-353	- 1.4	-350	- 1.4	-348
25	+24.9	-224	+24.9	-225	+24.9	-226	+24.9	-225
30	+46.7	-116	+46.7	-116	+46.9	-111	+46.8	-114
51	+95.7	+148	+95.7	+149	+95.7	+148	+95.7	+148
72	+73.4	+ 17	+73.4	+ 17	+73.4	+ 17	+73.4	+ 17

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE C3

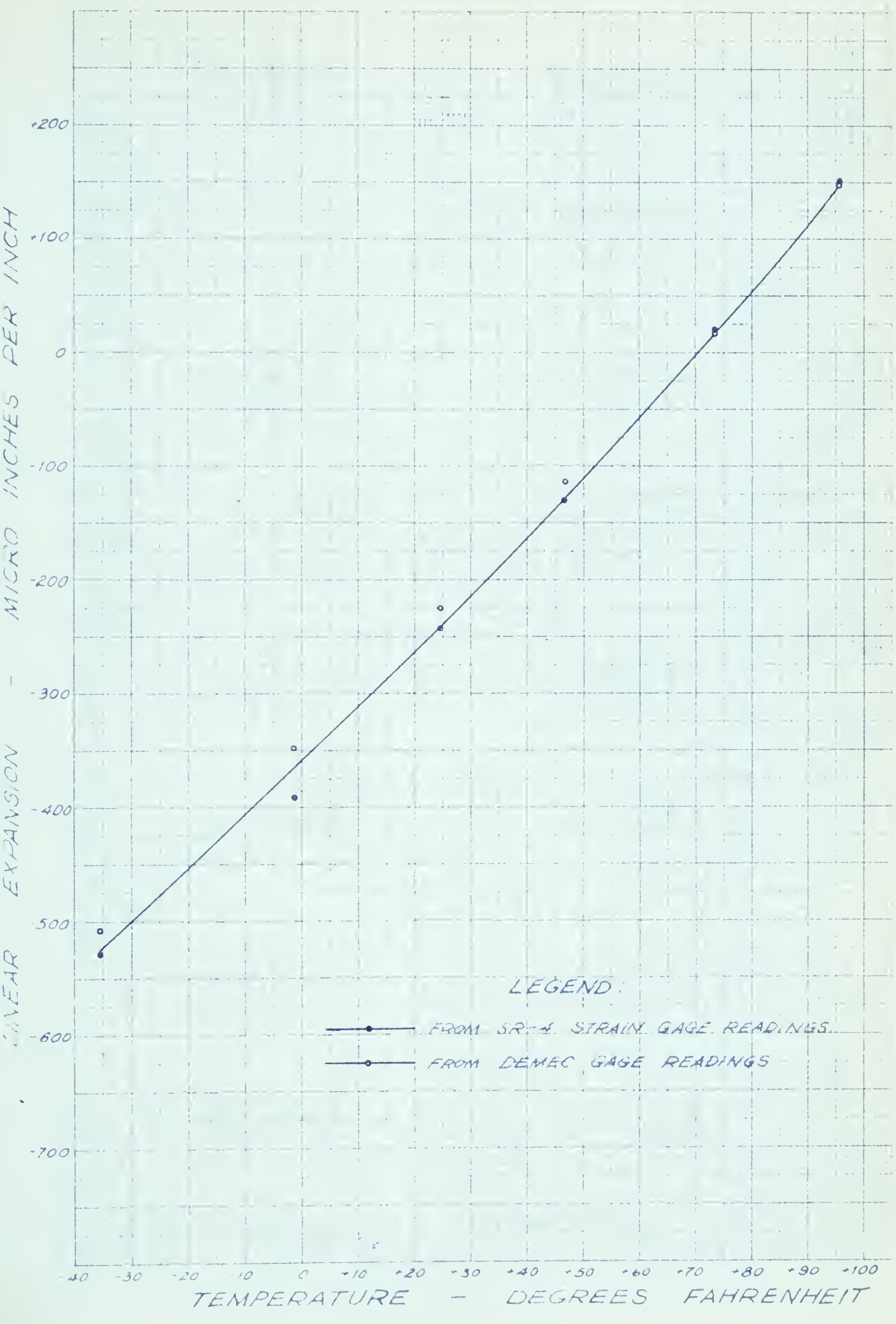


FIGURE 10

Table 14 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE C3.5

TIME+ HRS.	SPECIMEN 1 TEMP.* °F	SPECIMEN 1 $\delta L/L \times 10^6$‡	SPECIMEN 2 TEMP.* °F	SPECIMEN 2 $\delta L/L \times 10^6$‡	SPECIMEN 3 TEMP.* °F	SPECIMEN 3 $\delta L/L \times 10^6$‡	MEAN TEMP.* °F	MEAN $\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	- 35.6	- 505	- 35.6	- 511	- 35.6	- 536	- 35.6	- 517
5	- 1.7	- 370	- 1.6	- 377	- 1.6	- 398	- 1.6	- 382
25	+ 24.5	- 229	+ 24.8	- 239	+ 24.8	- 255	+ 24.7	- 241
30	+ 47.0	- 119	+ 47.0	- 127	+ 47.0	- 145	+ 47.0	- 130
51	+ 95.7	+ 154	+ 95.7	+ 150	+ 95.7	+ 148	+ 95.7	+ 151
72	+ 73.4	+ 18	+ 73.4	+ 20	+ 73.4	+ 22	+ 73.4	+ 20
REDUCED DEMEC STRAIN GAGE READINGS								
0	- 35.7	- 505	- 35.6	- 506	- 35.7	- 511	- 35.7	- 507
5	- 1.4	- 349	- 1.4	- 346	- 1.4	- 355	- 1.4	- 350
25	+ 24.9	- 231	+ 24.9	- 225	+ 24.9	- 229	+ 24.9	- 228
30	+ 46.9	- 118	+ 46.9	- 116	+ 47.0	- 119	+ 46.9	- 118
51	+ 95.7	+ 150	+ 95.7	+ 187	+ 95.7	+ 156	+ 95.7	+ 164
72	+ 73.4	+ 18	+ 73.4	+ 17	+ 73.4	+ 18	+ 73.4	+ 18

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE C 3.5

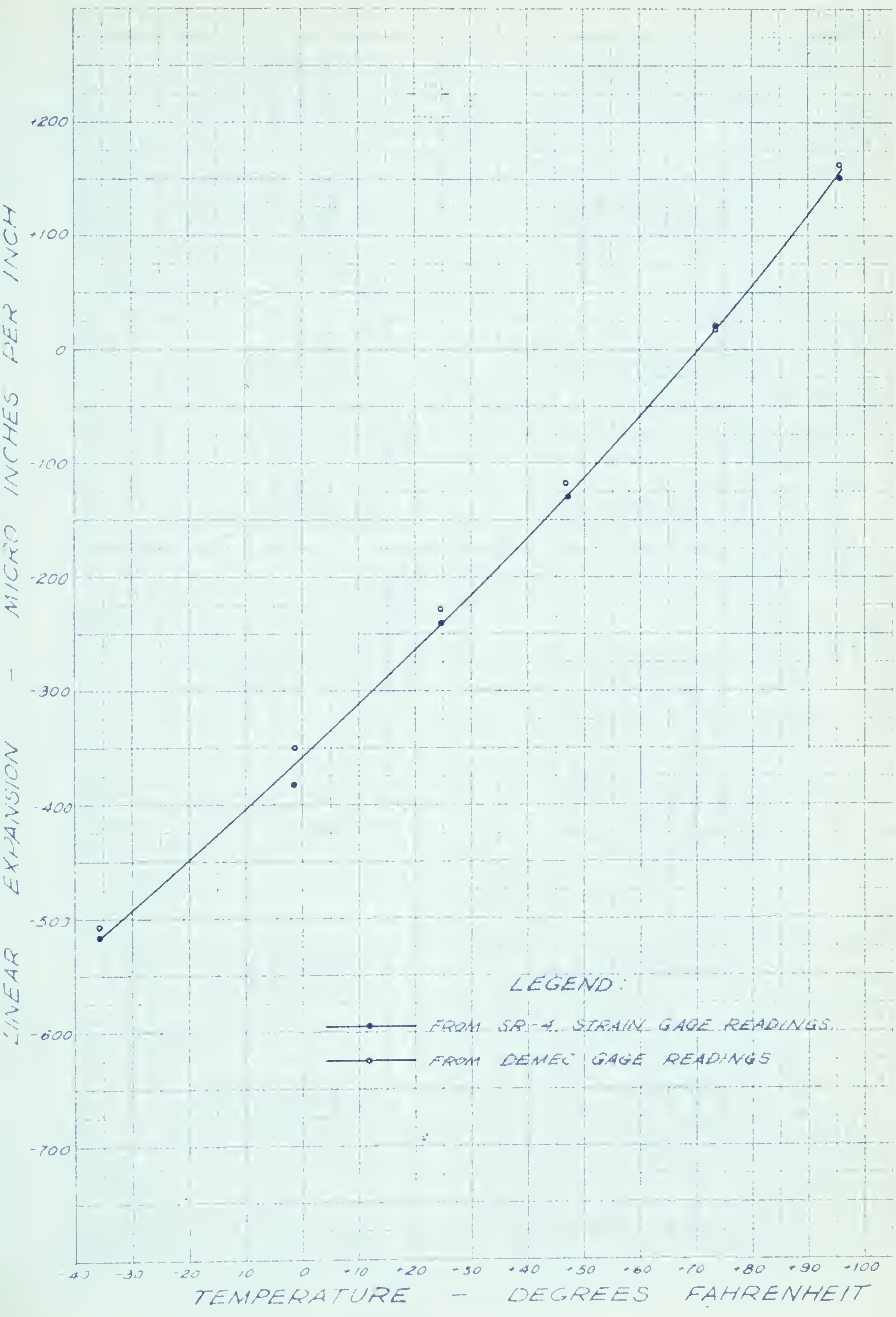


FIGURE 11

Table 15 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE C4

TIME† HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	- 36.9	- 547	- 36.9	- 555	- 36.9	- 570	- 36.9	- 557
5	- 5.9	- 400	- 5.9	- 406	- 5.8	- 415	- 5.9	- 407
26	+ 21.9	- 269	+ 21.8	- 270	+ 21.8	- 276	+ 21.8	- 272
30	+ 43.4	- 157	+ 43.4	- 158	+ 43.3	- 154	+ 43.4	- 156
50	+ 64.8	- 30	+ 64.8	- 30	+ 64.8	- 33	+ 64.8	- 31
56	+ 96.3	+ 172	+ 96.3	+ 171	+ 96.4	+ 177	+ 96.3	+ 173
125	+ 74.1	+ 17	+ 74.1	+ 18	+ 74.2	+ 20	+ 74.1	+ 18
REDUCED DEMEC STRAIN GAGE READINGS								
0	+ 75.5	+ 4	+ 75.6	- 3	+ 75.6	+ 1	+ 75.6	+ 1
16	- 37.1	- 527	- 37.0	- 532	- 36.6	- 542	- 36.9	- 534
21	- 6.0	- 386	- 5.9	- 380	- 5.8	- 390	- 5.9	- 385
42	+ 21.7	- 261	+ 21.4	- 254	+ 21.4	- 262	+ 21.5	- 259
46	+ 43.3	- 153	+ 43.0	- 171	+ 43.0	- 153	+ 43.1	- 159
66	+ 64.6	- 32	+ 64.6	- 32	+ 64.7	- 30	+ 64.6	- 31
72	+ 96.5	+ 160	+ 96.5	+ 156	+ 96.5	+ 150	+ 96.5	+ 155
149	+ 74.4	+ 3	+ 74.4	- 4	+ 74.4	0	+ 74.4	0

† Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE C4

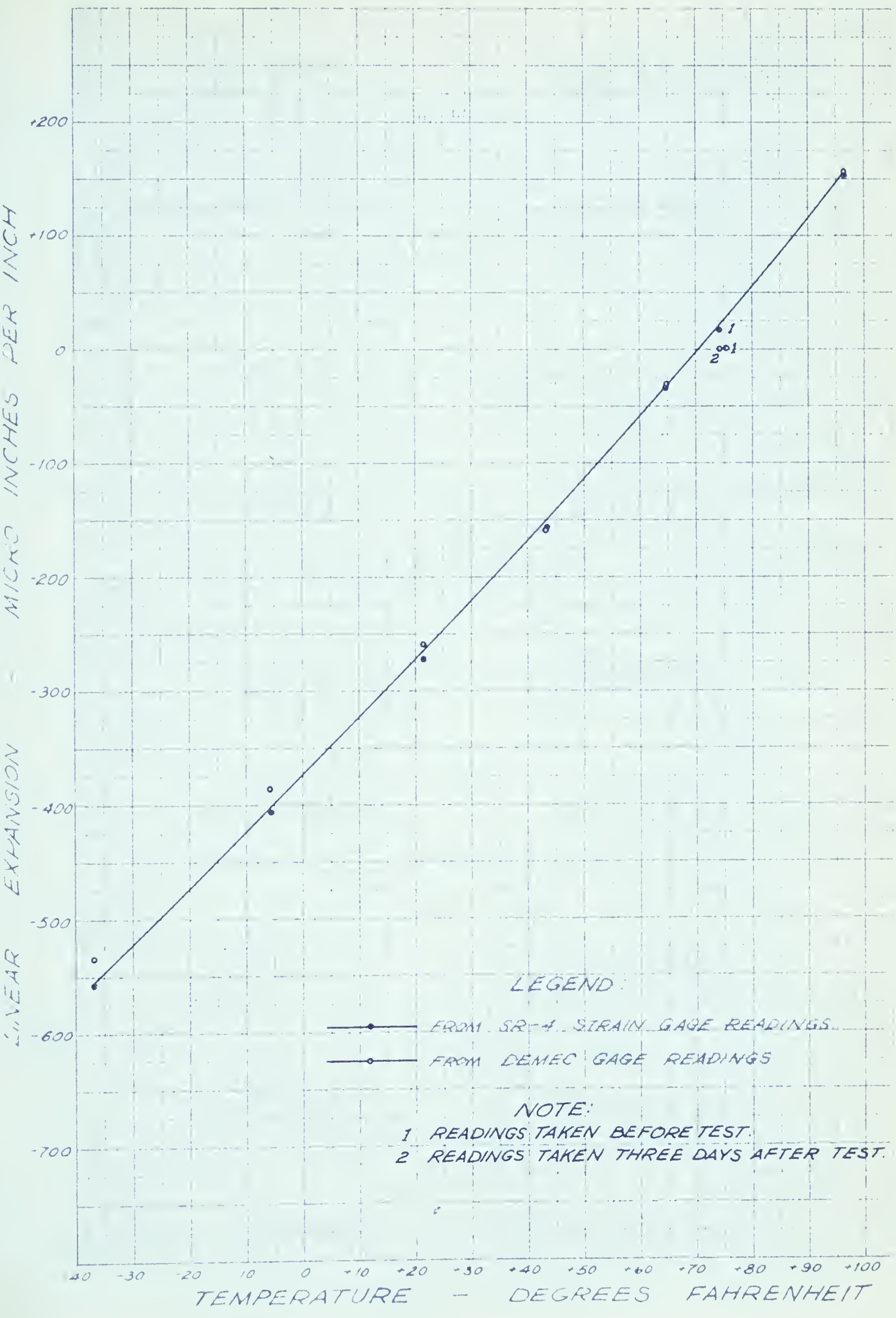


FIGURE 12

Table 16 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE C4.5

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	- 36.9	- 551	- 37.0	- 550	- 37.0	- 561	- 37.0	- 554
5	- 5.7	- 397	- 5.7	- 399	- 5.8	- 405	- 5.7	- 400
26	+ 21.9	- 271	+ 21.9	- 271	+ 21.9	- 271	+ 21.9	- 271
30	+ 43.4	- 159	+ 43.4	- 159	+ 43.4	- 156	+ 43.4	- 158
50	+ 64.8	- 32	+ 64.8	- 32	+ 64.7	- 33	+ 64.8	- 32
56	+ 96.6	+ 174	+ 96.6	+ 175	+ 96.6	+ 179	+ 96.6	+ 176
REDUCED DEMEC STRAIN GAGE READINGS								
0	+ 75.4	- 4	+ 75.5	- 5	+ 75.5	- 10	+ 75.5	- 6
16	- 36.5	- 546	- 36.5	- 542	- 36.4	- 533	- 36.5	- 540
21	- 5.8	- 390	- 5.8	- 386	- 5.3	- 385	- 5.6	- 387
42	+ 21.6	- 261	+ 21.7	- 256	+ 22.3	- 258	+ 21.9	- 258
46	+ 43.4	- 156	+ 43.4	- 157	+ 43.5	- 157	+ 43.4	- 157
66	+ 64.8	- 34	+ 64.9	- 31	+ 64.9	- 27	+ 64.9	- 31
72	+ 96.6	+ 176	+ 96.6	+ 164	+ 96.6	+ 145	+ 96.6	+ 162

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE C4.5

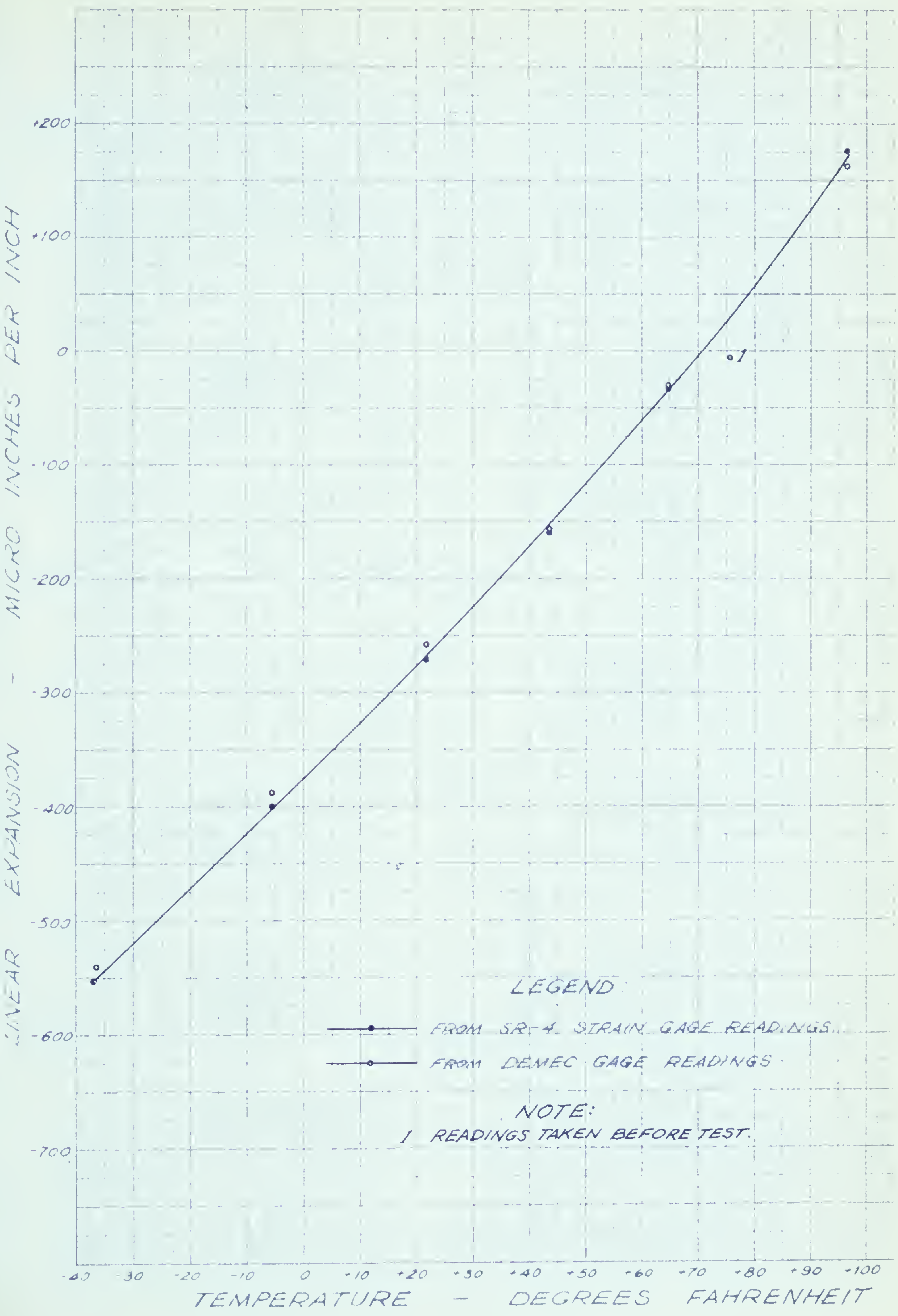


FIGURE 13

Table 17 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE C5

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	-37.4	-544	-37.4	-548	-37.4	-585	-37.4	-559
17	- 3.3	-382	- 3.3	-380	- 3.3	-408	- 3.3	-390
38	+22.2	-256	+22.1	-257	+22.1	-273	+22.1	-262
42	+36.7	-190	+36.5	-186	+36.5	-200	+36.6	-192
65	+74.2	+ 25	+74.2	+ 25	+74.3	+ 27	+74.2	+ 26
71	+94.5	+152	+94.5	+154	+94.4	+165	+94.5	+157
REDUCED DEMEC STRAIN GAGE READINGS								
0	-37.5	-538	-37.7	-542	-37.5	-564	-37.6	-548
17	- 3.6	-362	- 3.5	-370	- 3.5	-390	- 3.5	-374
38	+22.5	-246	+22.7	-246	+23.0	-260	+22.7	-251
42	+36.9	-181	+36.9	-182	+36.9	-192	+36.9	-185
65	+74.4	+ 25	+74.4	+ 25	+74.4	+ 25	+74.4	+ 25
71	+94.2	+149	+94.4	+146	+94.4	+144	+94.3	+146

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE C5

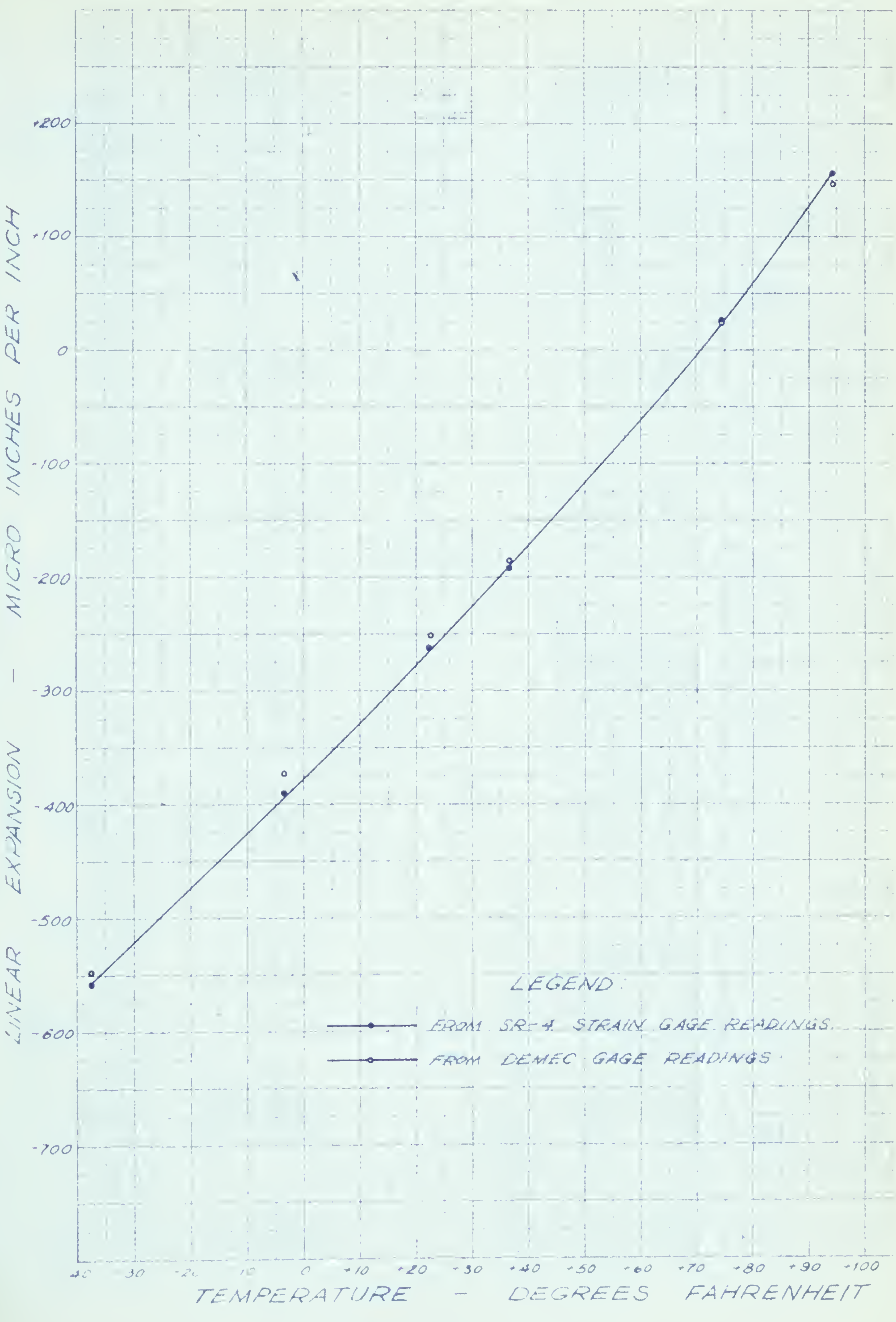


FIGURE 14

Table 18 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE R'3

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	+ 74.7	+ 24	+ 74.7	+ 28	+ 74.7	+ 24	+ 74.7	+ 25
24	- 38.1	- 469	- 38.1	- 502	- 38.1	- 475	- 38.1	- 482
29	- 3.7	- 324	- 3.7	- 339	- 3.6	- 326	- 3.7	- 330
53	+ 32.6	- 171	+ 32.6	- 180	+ 32.5	- 175	+ 32.6	- 175
74	+ 73.9	+ 19	+ 73.9	+ 20	+ 73.9	+ 21	+ 73.9	+ 20
103	+ 98.7	+ 181	+ 98.7	+ 188	+ 98.7	+ 183	+ 98.7	+ 184
REDUCED DEMEC STRAIN GAGE READINGS								
0	+ 74.8	+ 19	+ 74.8	+ 11	+ 74.8	+ 9	+ 74.8	+ 13
24	- 38.2	- 494	- 38.2	- 494	- 38.2	- 505	- 38.2	- 498
29	- 3.3	- 328	- 3.3	- 336	- 3.5	- 324	- 3.4	- 329
53	+ 32.6	- 172	+ 32.8	- 172	+ 32.7	- 177	+ 32.7	- 174
74	+ 74.1	+ 19	+ 74.1	+ 19	+ 74.2	+ 20	+ 74.1	+ 19
103	+ 98.8	+ 173	+ 98.8	+ 175	+ 99.3	+ 174	+ 99.0	+ 174

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE R'3

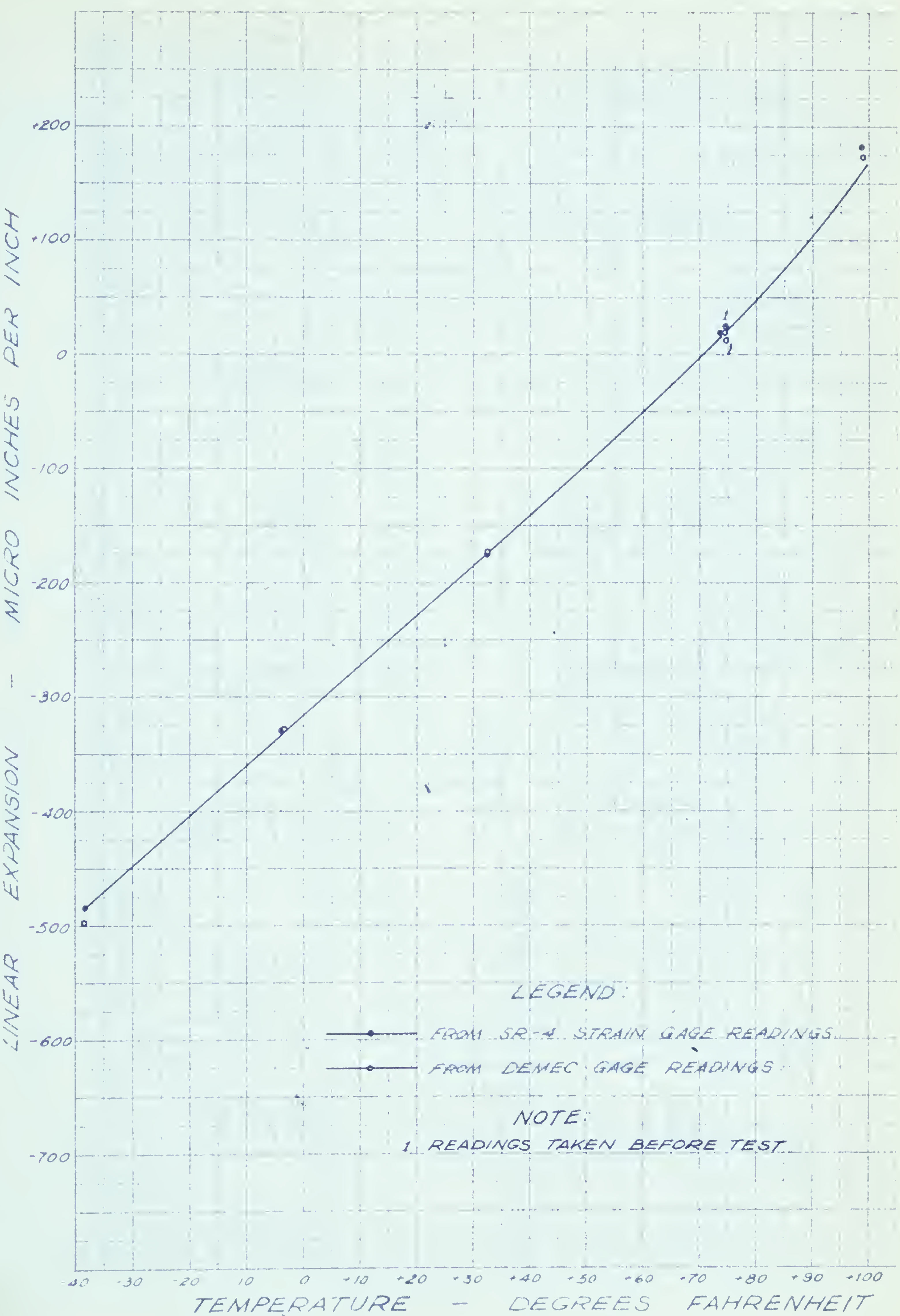


FIGURE 15

Table 19 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE R'3.5

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	δL/L × 10⁶‡	TEMP.* °F	δL/L × 10⁶‡	TEMP.* °F	δL/L × 10⁶‡	TEMP.* °F	δL/L × 10⁶‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	+ 74.8	+ 25	+ 74.8	+ 22	+ 74.8	+ 26	+ 74.8	+ 24
24	- 38.2	- 510	- 38.2	- 498	- 38.2	- 500	- 38.2	- 503
29	- 3.8	- 346	- 3.8	- 340	- 3.8	- 337	- 3.8	- 341
53	+ 32.7	- 180	+ 32.7	- 179	+ 32.6	- 176	+ 32.7	- 178
74	+ 74.2	+ 22	+ 74.2	+ 22	+ 74.1	+ 20	+ 74.2	+ 21
103	+ 98.7	+ 190	+ 98.7	+ 184	+ 98.7	+ 192	+ 98.7	+ 189
REDUCED DEMEC STRAIN GAGE READINGS								
0	+ 74.8	- 3	+ 74.8	+ 12	+ 74.8	- 1	+ 74.8	+ 3
24	- 38.2	- 526	- 38.0	- 496	- 38.2	- 520	- 38.1	- 514
29	- 3.3	- 352	- 3.3	- 327	- 3.3	- 345	- 3.3	- 341
53	+ 32.2	- 188	+ 32.0	- 175	+ 32.9	- 184	+ 32.4	- 182
74	+ 74.4	+ 22	+ 74.4	+ 21	+ 74.4	+ 22	+ 74.4	+ 22
103	+ 98.5	+ 168	+ 98.3	+ 182	+ 98.2	+ 180	+ 98.3	+ 177

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE R'3.5

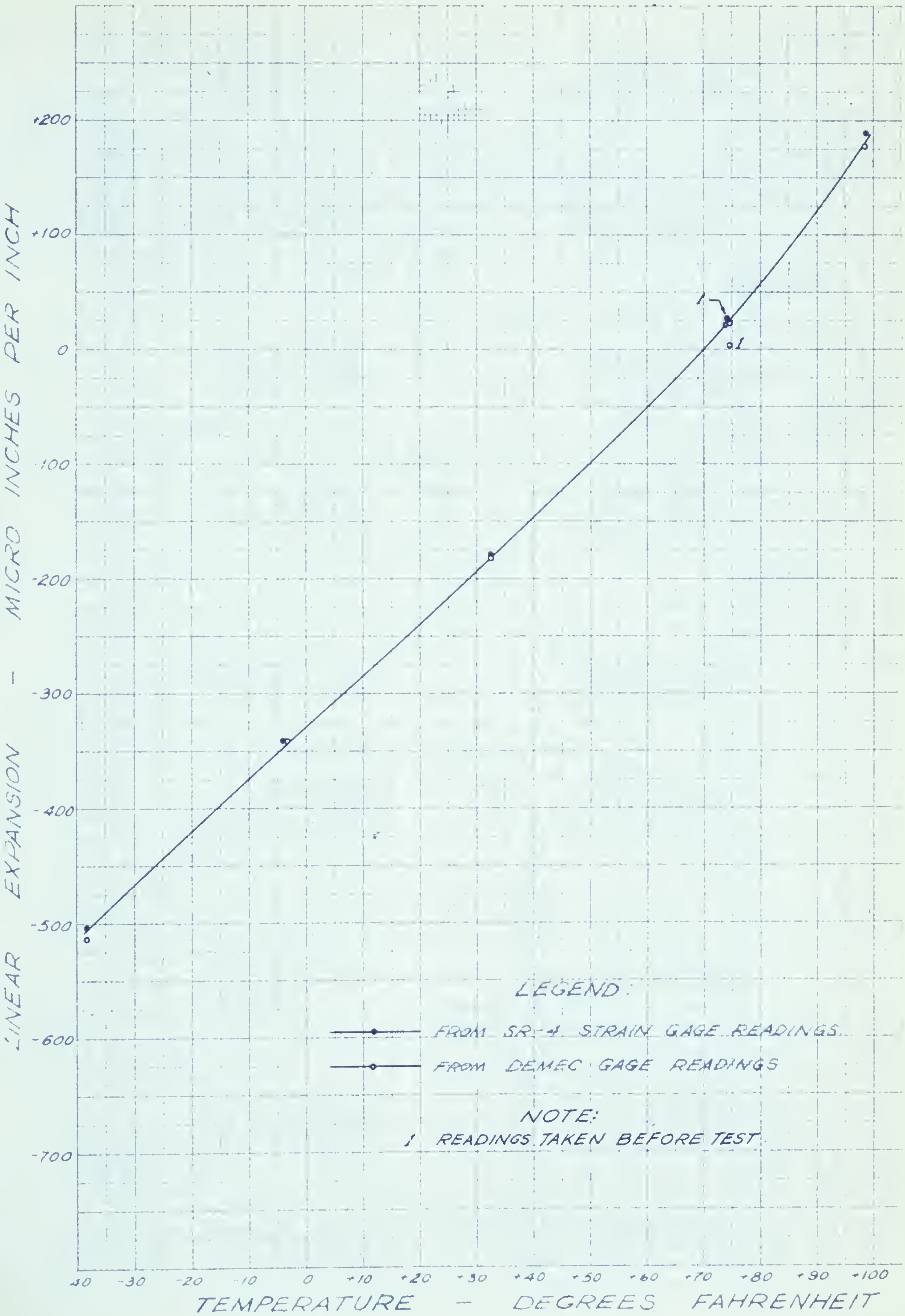


FIGURE 16

Table 20 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE R'4

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	+75.1	-53	+75.1	-52	+75.1	-53	+75.1	-53
17	-36.9	-559	-36.9	-575	-36.9	-597	-36.9	-577
22	-4.1	-354	-4.1	-370	-4.1	-380	-4.1	-368
44	+18.2	-249	+18.2	-263	+18.3	-266	+18.2	-259
48	+37.0	-163	+37.0	-174	+36.8	-174	+36.9	-170
69	+70.7	+3	+70.6	+4	+70.6	+4	+70.6	+4
76	+95.1	+150	+95.0	+150	+95.0	+153	+95.0	+151
REDUCED DEMEC STRAIN GAGE READINGS								
0	+75.1	-6	+75.1	-6	+75.1	-7	+75.1	-6
17	-37.0	-534	-37.0	-540	-36.8	-552	-36.9	-542
22	-3.9	-366	-3.9	-372	-3.7	-381	-3.8	-373
44	+18.2	-256	+18.2	-261	+18.5	-263	+18.3	-260
48	+36.8	-172	+36.8	-173	+36.5	-175	+36.7	-173
69	+71.0	+5	+71.2	+6	+71.1	+6	+71.1	+6
76	+95.2	+143	+95.2	+152	+95.2	+147	+95.2	+147

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE R'4

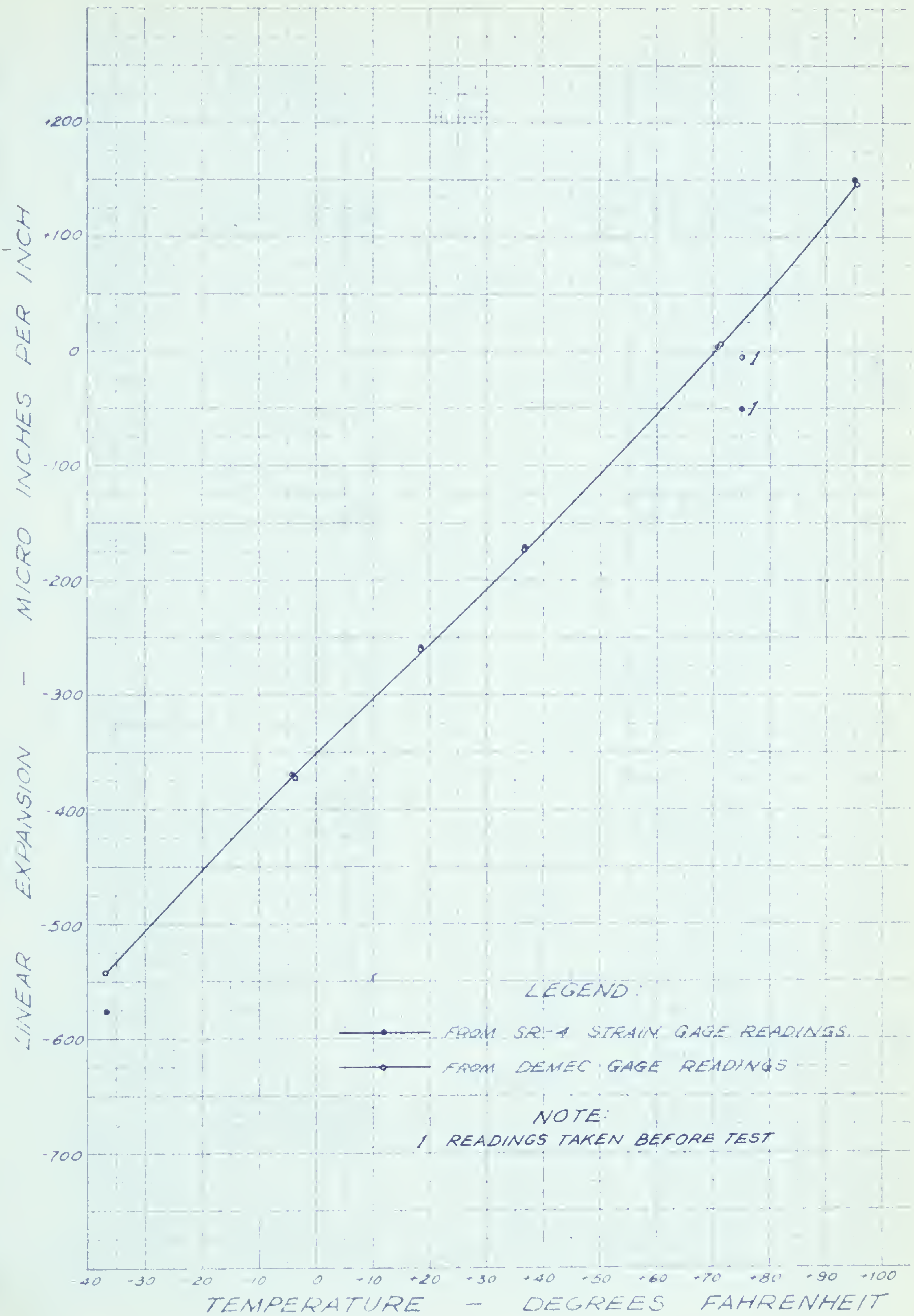


FIGURE 17

Table 21 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE R'4.5

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	+75.1	- 53	+75.1	- 55	+75.1	- 55	+75.1	- 54
17	-36.9	-596	-36.9	-605	-36.9	-614	-36.9	-605
22	- 4.1	-376	- 4.1	-379	- 4.1	-385	- 4.1	-380
44	+18.3	-262	+18.3	-268	+18.3	-270	+18.3	-267
48	+36.8	-173	+36.8	-183	+36.8	-183	+36.8	-180
69	+71.2	+ 7	+71.2	+ 7	+71.2	+ 7	+71.2	+ 7
76	+95.3	+157	+95.3	+152	+95.3	+155	+95.3	+155
REDUCED DEMEC STRAIN GAGE READINGS								
0	+75.3	- 10	+75.3	- 5	+75.3	- 11	+75.3	- 9
17	-36.4	-557	-36.1	-534	-36.1	-549	-36.2	-547
22	- 3.9	-383	- 3.9	-373	- 3.9	-375	- 3.9	-377
44	+18.6	-256	+18.6	-258	+19.0	-263	+18.7	-259
48	+36.8	-191	+36.9	-182	+37.0	-180	+36.9	-184
69	+71.2	+ 7	+71.2	+ 6	+71.3	+ 7	+71.2	+ 7
76	+95.2	+152	+95.2	+144	+95.2	+157	+95.2	+151

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE R'4.5

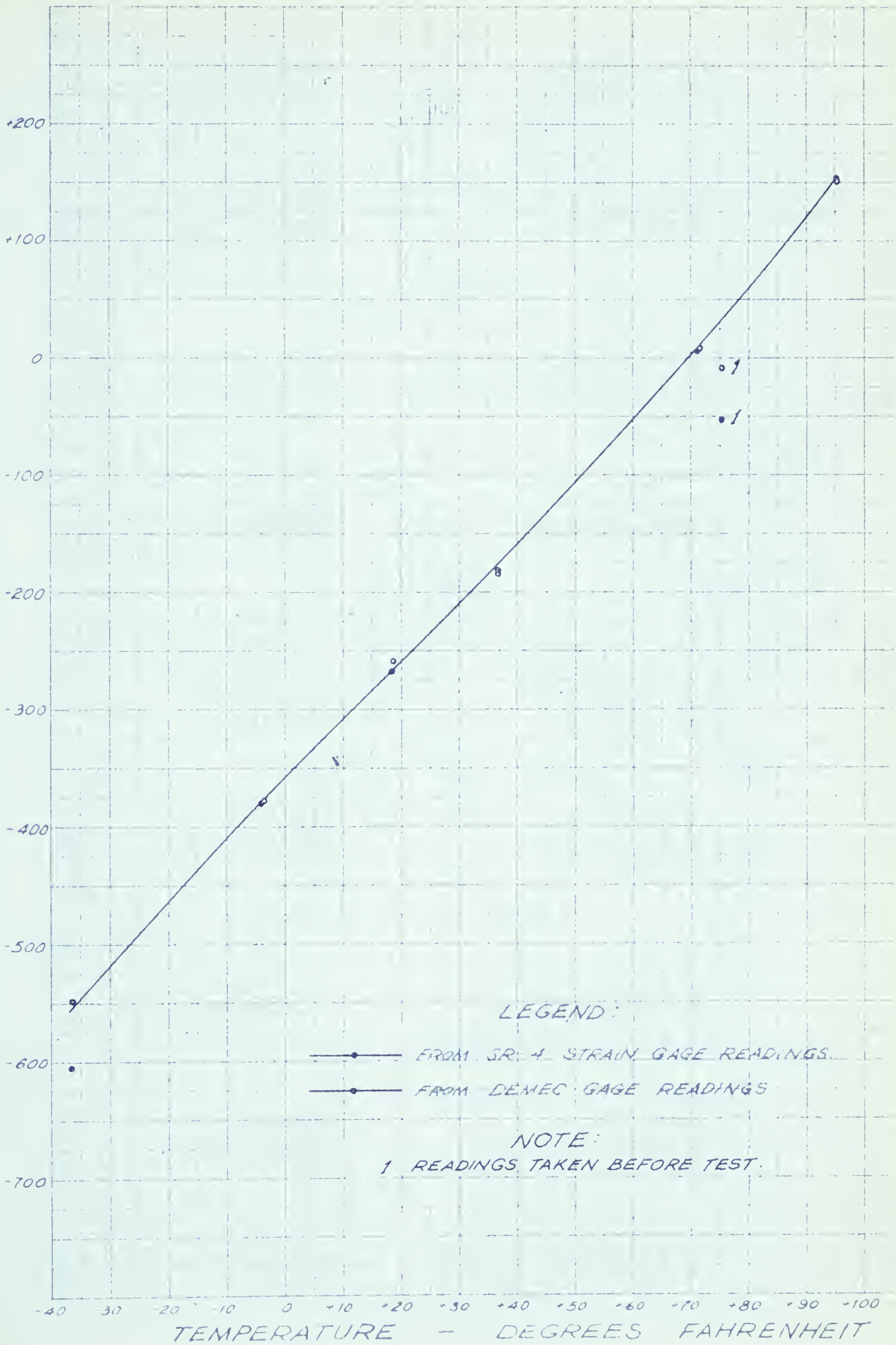


FIGURE 18

Table 22 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE R'5

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	- 36.9	- 549	- 36.8	- 534	- 36.8	- 513	- 36.8	- 532
4	- 8.0	- 406	- 8.3	- 399	- 8.0	- 377	- 8.1	- 394
23	+ 16.9	- 270	+ 17.0	- 268	+ 17.2	- 254	+ 17.0	- 264
27	+ 40.4	- 157	+ 40.3	- 160	+ 40.4	- 150	+ 40.4	- 156
47	+ 70.4	+ 4	+ 70.4	+ 5	+ 70.4	+ 7	+ 70.4	+ 5
51	+ 97.1	+ 171	+ 97.2	+ 170	+ 97.7	+ 175	+ 97.3	+ 172
REDUCED DEMEC STRAIN GAGE READINGS								
0	- 36.9	- 538	- 36.8	- 547	- 36.0	- 546	- 36.6	- 544
4	- 8.0	- 399	- 8.0	- 404	- 8.0	- 398	- 8.0	- 400
23	+ 16.4	- 266	+ 16.9	- 271	+ 17.1	- 267	+ 16.8	- 268
27	+ 40.4	- 161	+ 40.4	- 161	+ 40.6	- 159	+ 40.5	- 160
47	+ 70.5	+ 3	+ 70.5	+ 3	+ 70.6	+ 3	+ 70.5	+ 3
51	+ 97.2	+ 165	+ 97.2	+ 180	+ 97.5	+ 165	+ 97.3	+ 170

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE R'5

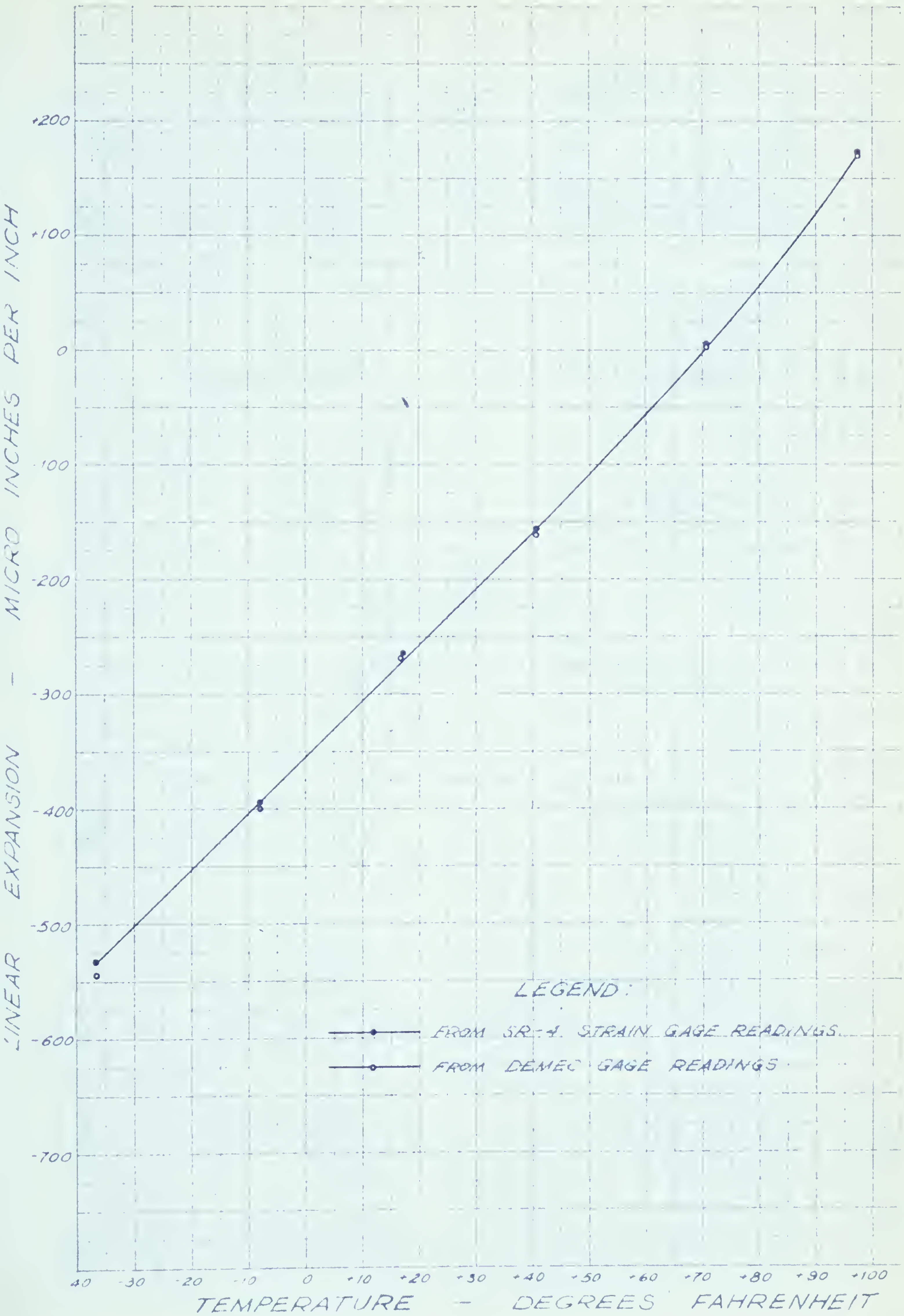


FIGURE 19

Table 23 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE R3

TIME† HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	δL/L × 10⁶‡	TEMP.* °F	δL/L × 10⁶‡	TEMP.* °F	δL/L × 10⁶‡	TEMP.* °F	δL/L × 10⁶‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	+75.0	+12	+75.0	+10	+75.0	+16	+75.0	+13
21	-36.9	-449	-36.9	-459	-36.9	-476	-36.9	-461
29	-2.6	-327	-2.7	-335	-2.4	-342	-2.6	-335
43	+18.8	-242	+19.0	-250	+19.0	-257	+18.9	-250
47	+41.4	-141	+41.6	-146	+42.0	-153	+41.7	-147
64	+73.8	+20	+73.8	+21	+73.8	+21	+73.8	+21
70	+94.2	+147	+94.2	+148	+94.2	+144	+94.2	+146
REDUCED DEMEC STRAIN GAGE READINGS								
0	+75.0	+7	+75.0	+12	+75.0	+8	+75.0	+9
21	-37.0	-472	-36.5	-465	-36.3	-466	-36.6	-468
29	-2.6	-339	-2.3	-333	-1.1	-333	-2.0	-335
43	+18.9	-256	+19.3	-252	+19.3	-253	+19.2	-254
47	+41.3	-143	+41.8	-139	+41.8	-142	+41.6	-141
64	+74.0	+20	+74.0	+20	+74.0	+20	+74.0	+20
70	+94.1	+137	+94.1	+140	+93.7	+138	+94.0	+138

† Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE R3

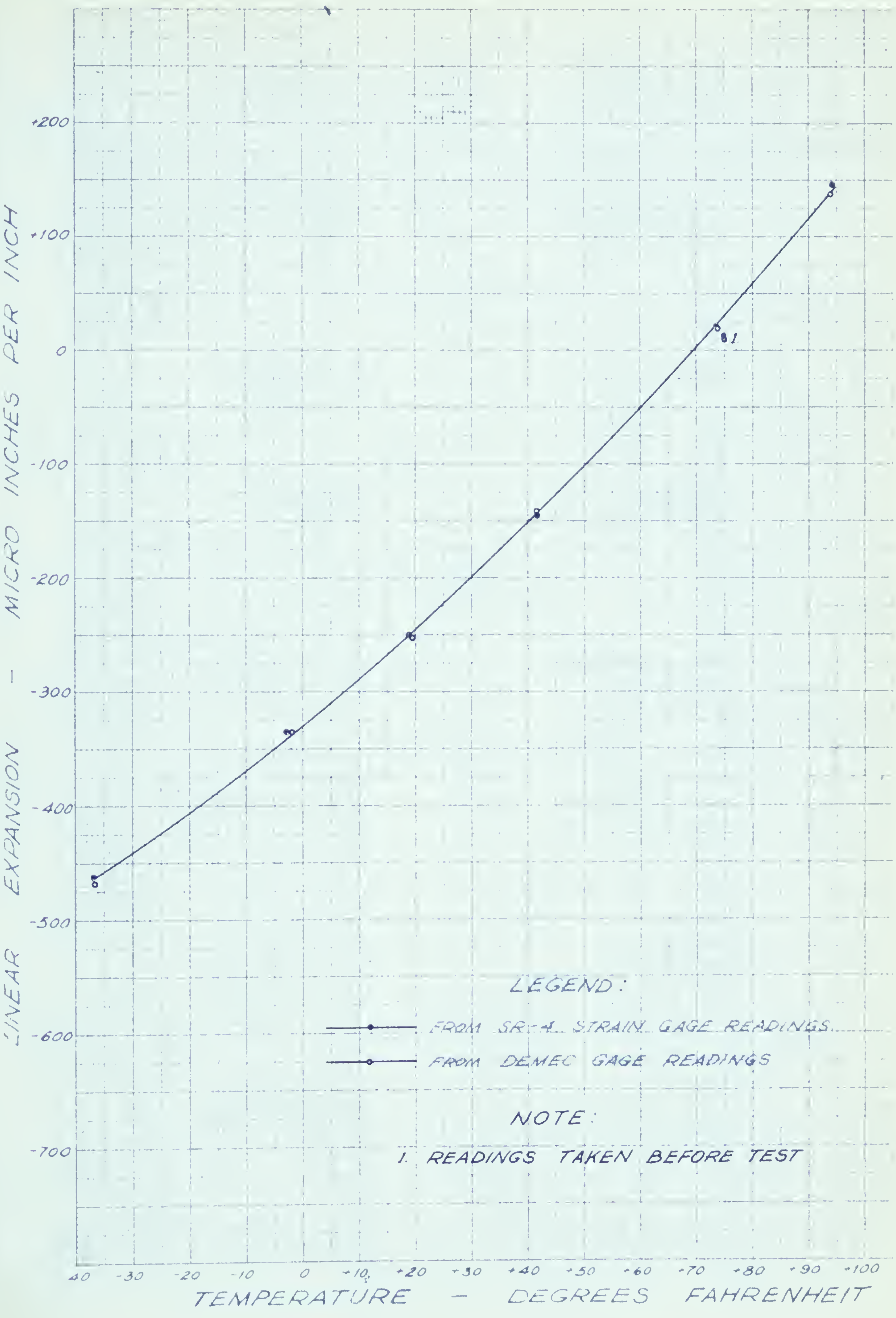


FIGURE 20

Table 24 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE R5

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡	TEMP.* °F	$\delta L/L \times 10^6$‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	+ 75.0	- 8	+ 75.0	- 15	+ 75.0	- 1	+ 75.0	- 8
21	- 37.3	- 477	- 37.2	- 483	- 37.2	- 465	- 37.2	- 475
29	- 2.7	- 341	- 2.6	- 339	- 2.6	- 337	- 2.6	- 339
43	+ 18.9	- 259	+ 19.0	- 263	+ 19.0	- 257	+ 19.0	- 260
47	+ 41.4	- 160	+ 41.4	- 159	+ 41.6	- 154	+ 41.5	- 158
64	+ 73.8	+ 22	+ 73.8	+ 22	+ 73.8	+ 21	+ 73.8	+ 22
70	+ 94.2	+ 158	+ 94.2	+ 153	+ 94.2	+ 148	+ 94.2	+ 153
REDUCED DEMEC STRAIN GAGE READINGS								
0	+ 75.0	- 7	+ 75.0	- 8	- 75.0	+ 1	+ 75.0	- 5
21	- 37.0	- 492	- 36.7	- 478	- 36.7	- 493	- 36.8	- 488
29	- 2.3	- 352	- 2.3	- 338	- 2.3	- 345	- 2.3	- 345
43	+ 17.8	- 271	+ 18.5	- 265	+ 18.5	- 271	+ 18.3	- 269
47	+ 41.7	- 155	+ 41.3	- 153	+ 41.5	- 154	+ 41.5	- 154
64	+ 74.2	+ 23	+ 74.2	+ 23	+ 74.2	+ 23	+ 74.2	+ 23
70	+ 93.1	+ 146	+ 93.2	+ 147	+ 93.4	+ 124	+ 93.2	+ 139

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF CONCRETE TYPE R 5

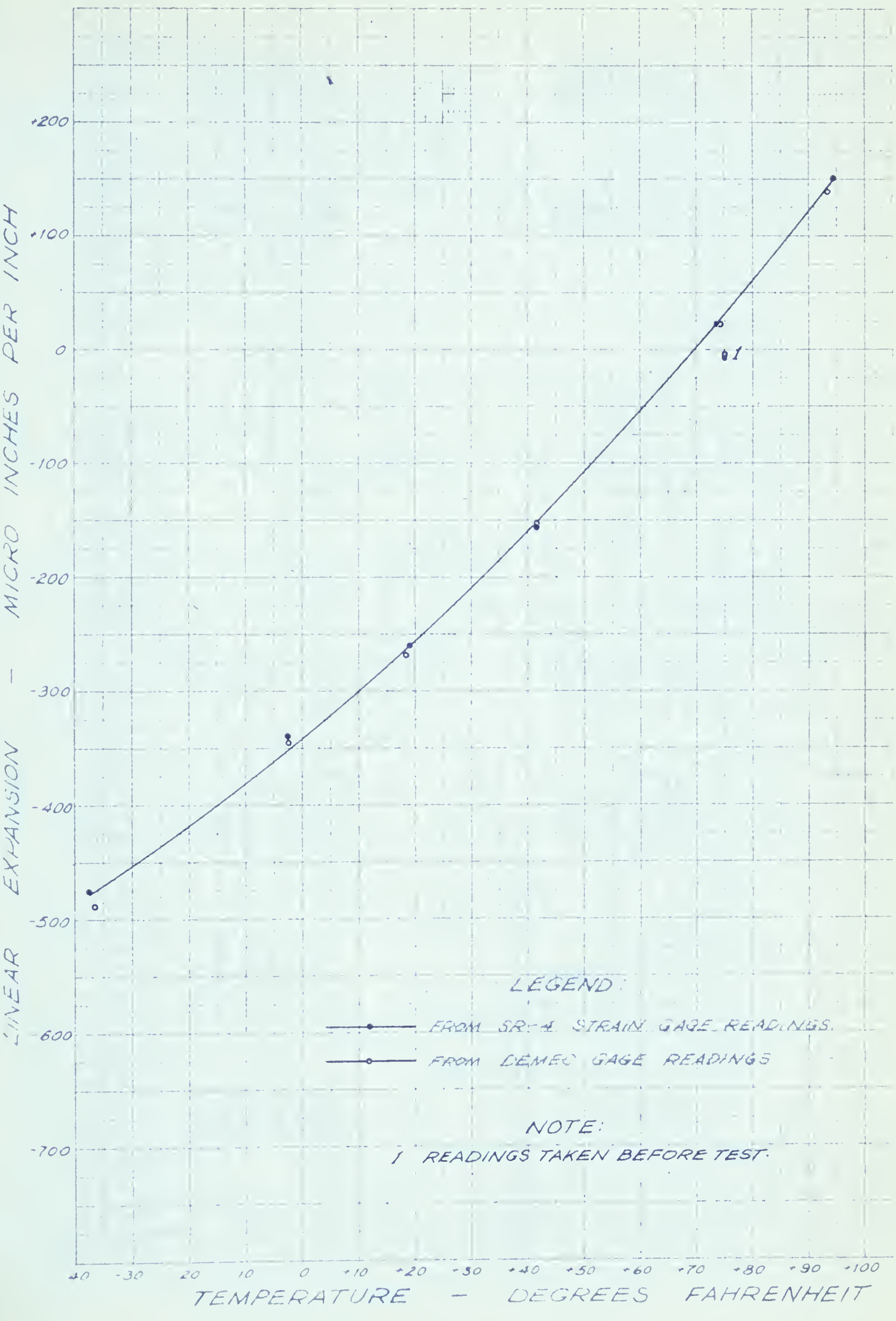


FIGURE 21

Table 25 REDUCED THERMAL EXPANSION DATA REINFORCING STEEL - NO.8 BAR

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	δL/L × 10⁶‡	TEMP.* °F	δL/L × 10⁶‡	TEMP.* °F	δL/L × 10⁶‡	TEMP.* °F	δL/L × 10⁶‡
REDUCED SR-4 STRAIN GAGE READINGS								
	- 38.4	- 660	- 38.4	- 648			- 38.4	- 654
	- 10.1	- 497	- 10.1	- 494			- 10.1	- 495
	+ 16.3	- 337	+ 16.4	- 332			+ 16.4	- 335
	+ 43.6	- 165	+ 43.7	- 166			+ 43.7	- 165
	+ 74.5	+ 29	+ 74.5	+ 29			+ 74.5	+ 29
	+ 93.3	+ 162	+ 93.2	+ 156			+ 93.3	+ 159
REDUCED DEMEC STRAIN GAGE READINGS								
	- 38.5	- 669	- 38.5	- 661			- 38.5	- 665
	- 10.4	- 497	- 9.2	- 491			- 9.8	- 494
	+ 16.9	- 342	+ 16.9	- 324			+ 16.9	- 333
	+ 43.9	- 172	+ 43.9	- 159			+ 43.9	- 165
	+ 74.9	+ 32	+ 74.9	+ 29			+ 74.9	+ 30
	+ 93.2	+ 138	+ 93.2	+ 146			+ 93.2	+ 142

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

THERMAL EXPANSION OF REINFORCING STEEL

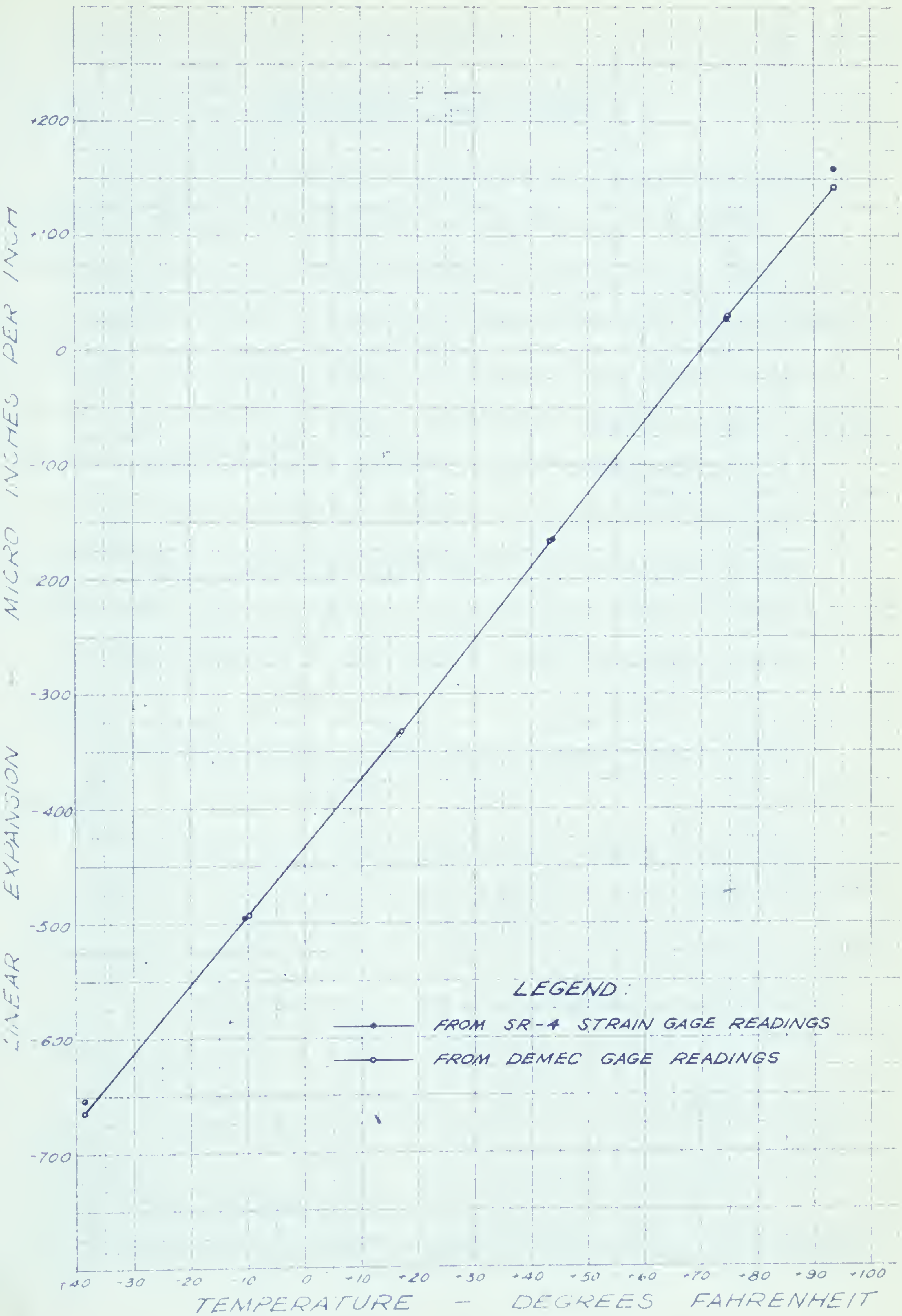


FIGURE 22

CHAPTER VI

DISCUSSION OF TEST RESULTS

The methods employed in obtaining the results are new in many respects, but precedence had been set in the basic methods of instrumentation. Electrical resistance strain gages had been successfully used by Callan (9) and Hidnert (26) in measuring the coefficient of thermal expansion of aggregates and glass respectively. Success in the use of the "Demec" gage in measuring strains in concrete structures had been reported by Base (24, 25). Further proof of the adequacy of the methods of instrumentation is given in Appendix II in which the thermal expansion characteristics as determined by these methods for samples of vitreous silica glass and steel are compared to the characteristics as determined separately by other investigators.

Several observations are readily discernible in the preceding figures:

1. The unit length-temperature relationships do not exhibit any pronounced changes upon freezing which would be a result of the conversion of water to ice within the pore structure of the concrete.

2. An upward curvature of the length-temperature relationship is exhibited by almost all of the concrete types.

3. The phenomenon of residual expansion or "permanent set" is evident for all concrete types for which initial readings were taken at room temperature (Figures 8, 11, 12, 14 to 17, and 20).

4. The mean coefficient of thermal expansion for the reinforcing

steel bar is 6.1 micro-inches per inch per degree Fahrenheit (Figure 22).

No sudden discontinuity in the unit length-temperature relationships exist at freezing because the specimens were in a relatively dry state when tested and the rate of temperature change during the tests was slow. Results obtained in tests performed by Valore (8) and Mitchell (12) indicated conclusively that departures from linearity as a result of the conversion of water to ice within the pore structure of concrete were practically non-existent when the rate of temperature change was slow and the moisture content of the concrete was well below critical saturation (the critical degree of saturation as reported by Mitchell is about 90% of vacuum saturation for non-air entrained concretes and approximately equal to the moisture content obtained by fog curing). Although the degree of vacuum saturation for the specimens tested in the present investigation was not determined, the literature (8, 12) indicates conclusively that the drying conditions were sufficient to produce moisture contents which were well below critical saturation.

The upward curvature of the length-temperature relationship is in agreement with the findings of Hatt (1) who measured the coefficient of thermal expansion between 27°F and 94°F for air dry concrete produced from Indiana sand and gravel. Willis and DeReus (2) found that the thermal coefficient for limestone increased rapidly with temperature within the range 37°F to 140°F. Both Mitchell (12) and Bonnel (10) reported a marked non-linear length-temperature relationship for neat cement. These findings may be linked with the findings of this investigation.

The phenomenon of residual expansion or "permanent set" produced by a single cycle of freezing and thawing was reported by Valore (8) and confirmed by Mitchell (12) for concretes in a "partially saturated" condition (slightly below critical saturation). Residual expansions were reported for concretes which were a little below or above critical saturation, but little or no residual expansion was reported for concretes in a very dry condition. The magnitude of the residual expansion as obtained in the present investigation averages at 25 to 30 micro-inches per inch which is generally of the same order reported by Valore for "partially saturated" concrete tested in a slow cycle between 40°F and -20°F. No indication of the numerical magnitude of the "permanent set" was given by Mitchell.

The coefficient of thermal expansion of reinforcing steel is generally assumed to be 6.5 micro-inches per inch per degree Fahrenheit in reinforced concrete design, although values of 6.1, 6.7 and 7.3 are tabulated for soft, medium and hard steels respectively in the "Steel Construction Manual" of the "American Institute of Steel Construction". The value obtained for the structural grade reinforcing steel agrees precisely with the value given for soft steel.

Comparisons of the thermal expansion characteristics for the various design strengths of each concrete type are shown graphically in Figures 23 to 26. The mean thermal coefficient tends to increase with design strength, probably as a direct result of the increase in cement factor. The mean thermal coefficients as indicated by the slope of each curve for the entire temperature range; the range below freezing (32°F); and the range above freezing are tablated in Table 26.

COMPARISON OF THERMAL EXPANSION CHARACTERISTICS - CONCRETE TYPE E

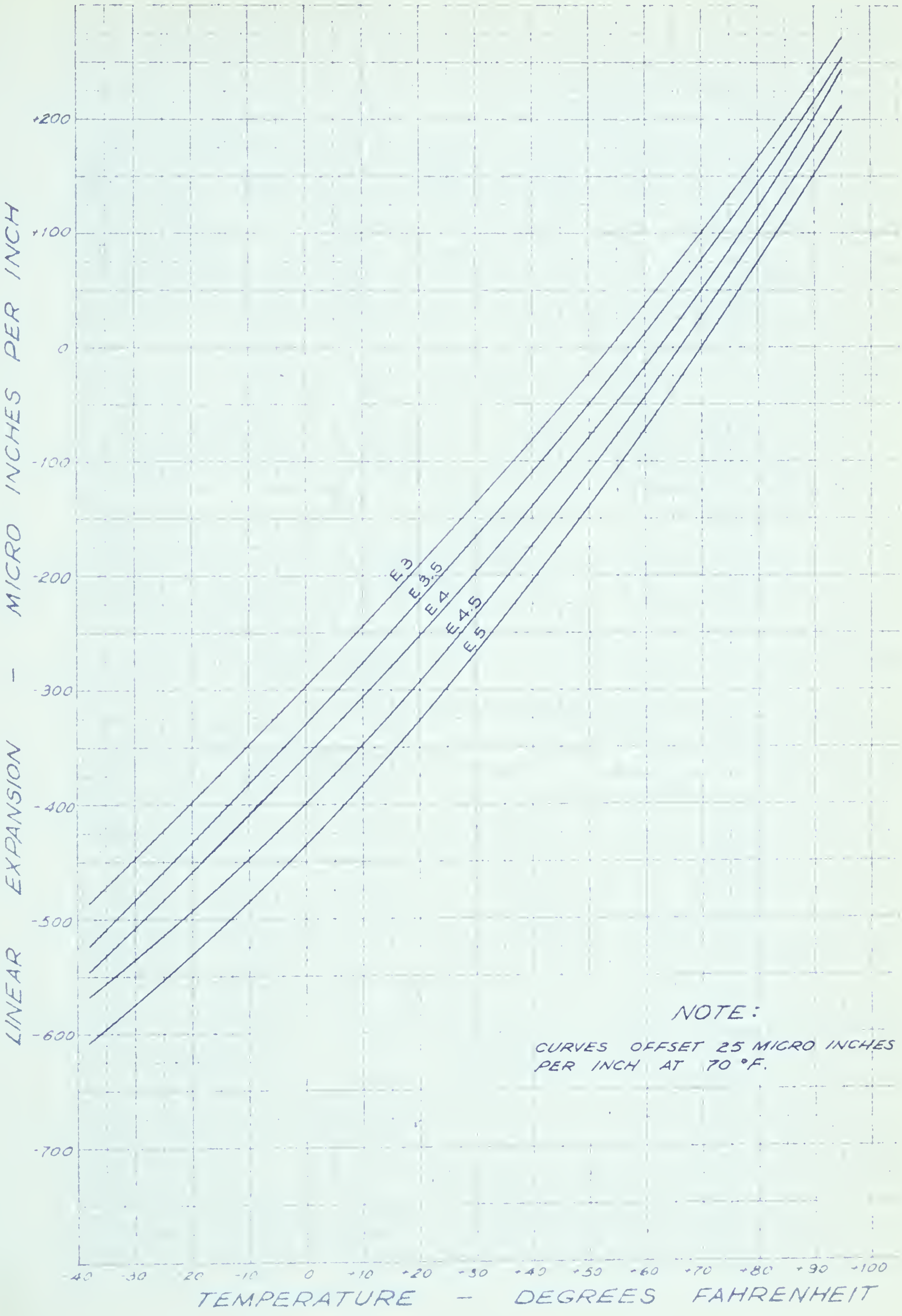


FIGURE 23

COMPARISON OF THERMAL EXPANSION CHARACTERISTICS
— CONCRETE TYPE C

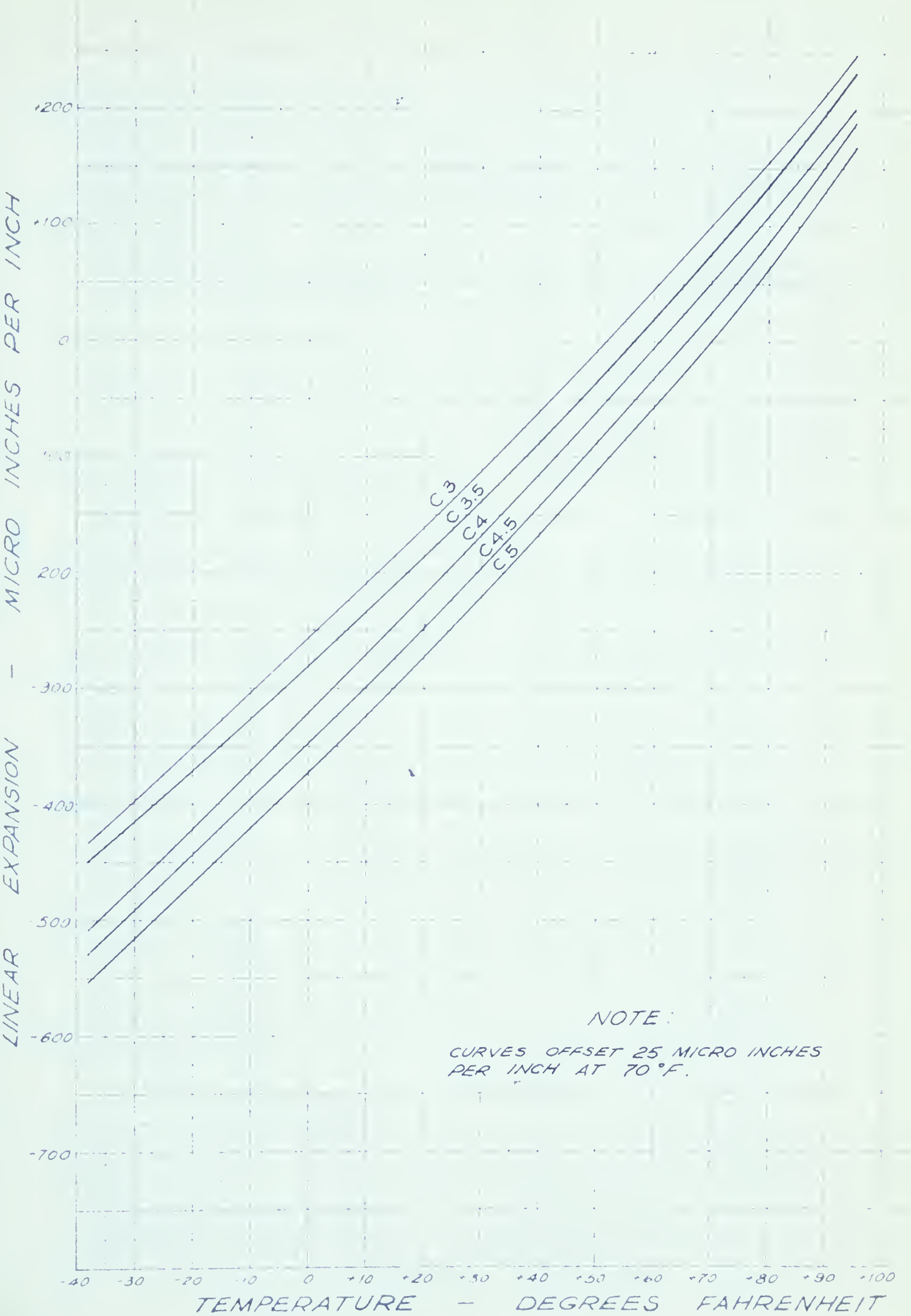


FIGURE 24

COMPARISON OF THERMAL EXPANSION CHARACTERISTICS
— CONCRETE TYPE R'

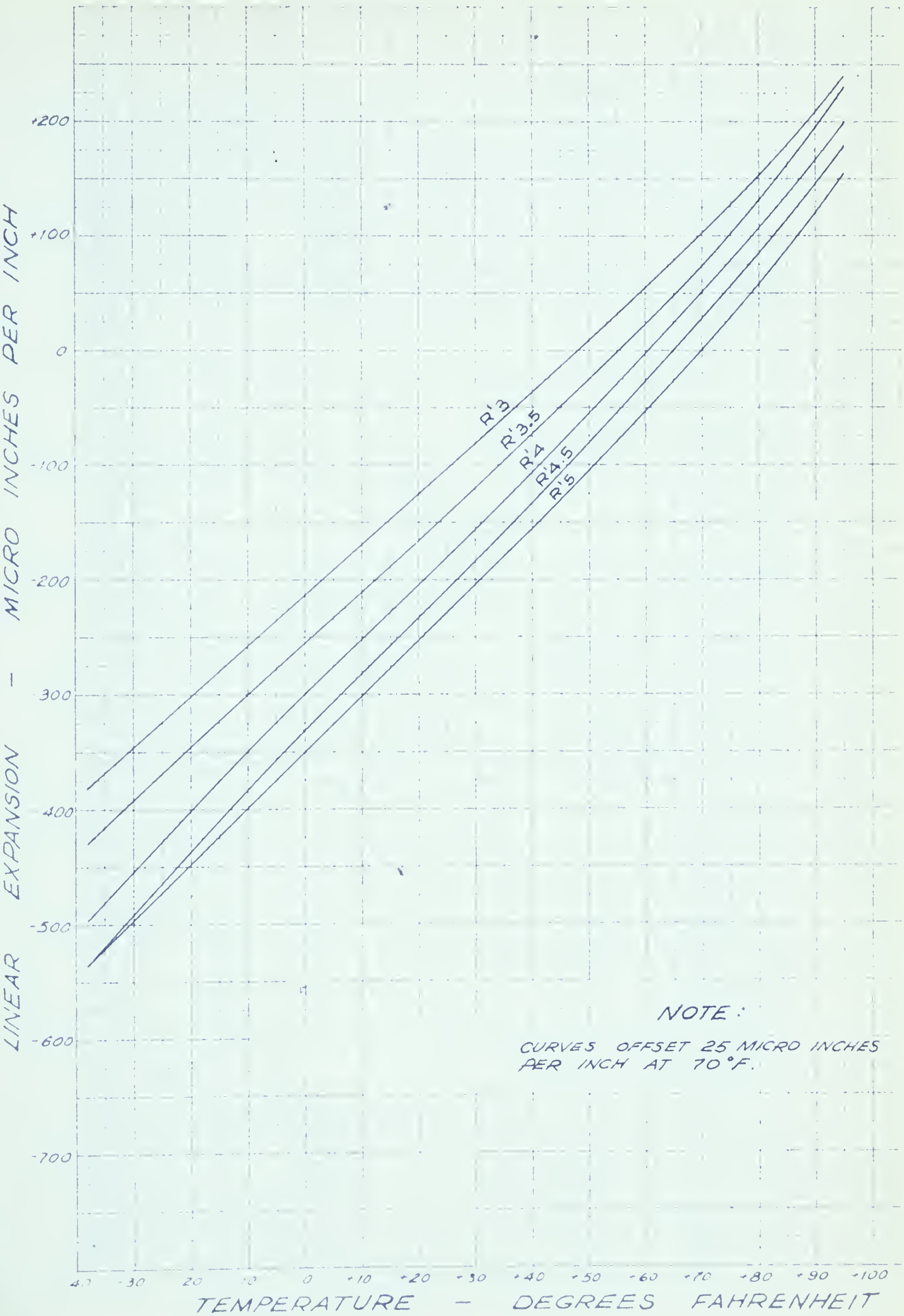


FIGURE 25

COMPARISON OF THERMAL EXPANSION CHARACTERISTICS — CONCRETE TYPE R

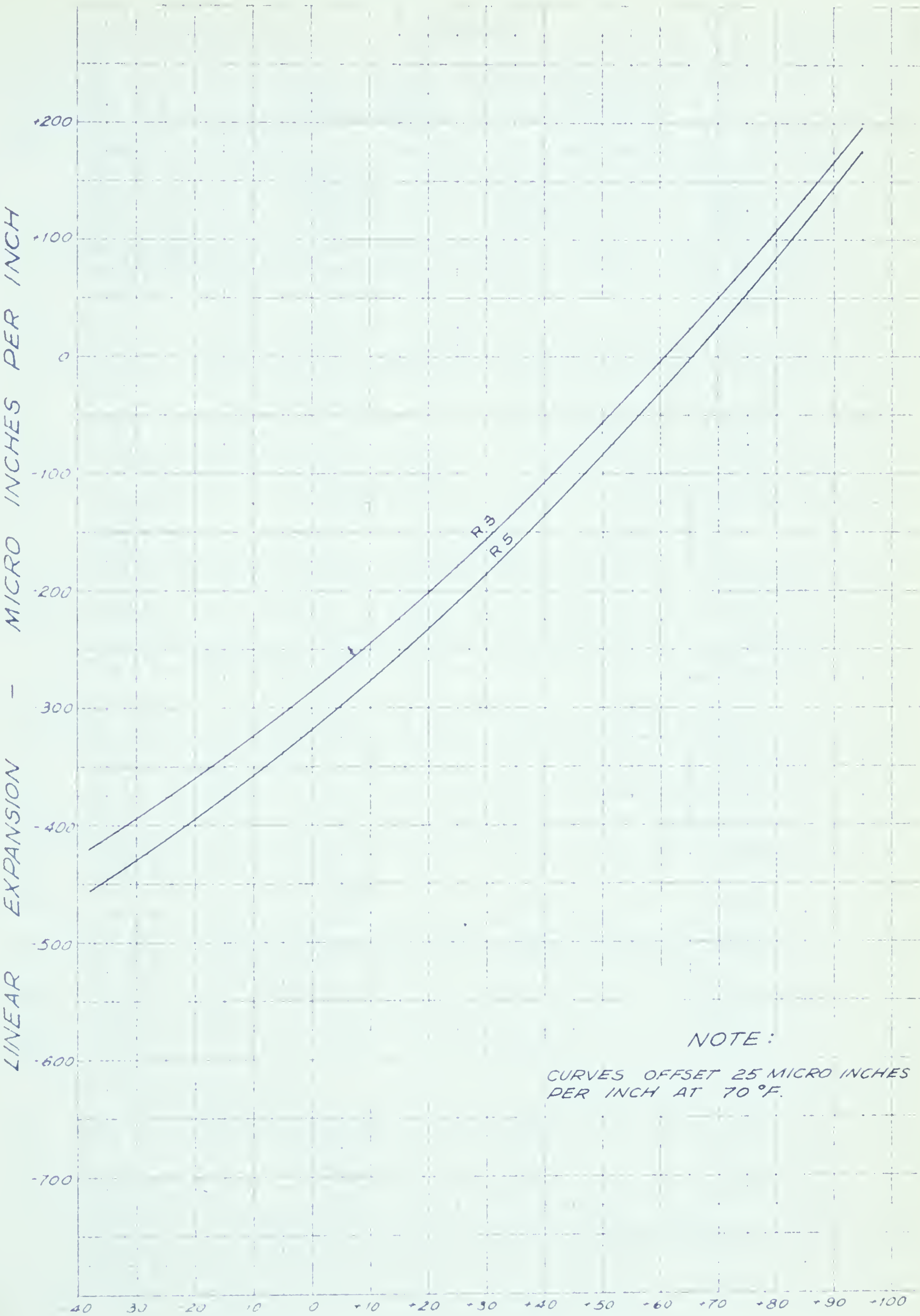


FIGURE 26

Table 26

Concrete Type	Mean Thermal Coefficient (Micro-inches per Inch per ^{o}F)		
	Entire Temperature Range	Below Freezing	Above Freezing
E3	5.6	5.1	6.3
E3.5	5.7	5.2	6.5
E4	5.8	5.2	6.8
E4.5	5.9	5.0	6.9
E5	6.1	5.1	7.0
C3	5.1	4.7	5.4
C3.5	5.1	4.6	5.6
C4	5.3	5.0	5.8
C4.5	5.3	4.9	5.8
C5	5.3	4.9	5.9
R'3	4.6	4.4	4.8
R'3.5	4.8	4.5	5.2
R'4	5.1	4.9	5.5
R'4.5	5.1	4.9	5.5
R'5	5.1	4.9	5.5
R3	4.7	3.9	5.4
R5	4.8	4.1	5.5

These coefficients were obtained by measuring the slope of a secant which was drawn on each curve to join the +80°F and -20°F points; the -32°F and +32°F points; and the +32°F to +90°F points respectively. This method was chosen in order to retain a uniform method of evaluating the slopes for all of the curves. An examination of the curves will reveal that the slopes of these secants represent the mean coefficients very closely.

The mean thermal coefficients which were obtained are compared with the cement factor in Figure 27. The tendency for the mean thermal coefficient to increase with the cement factor can be clearly seen. The chief exception to this trend is shown by concrete type E below freezing. The explanation for this behavior is not evident. In view of the variation in the fine and coarse aggregate proportions with strength, and the probable difference in the thermal expansion properties of the fine and coarse aggregates, a comparison of this type is qualitative at best. The increase in the thermal coefficient of concrete with the richness of mix has been reported by many other investigators.

The Calgary aggregates appear to produce concretes of lower thermal coefficient than do the Edmonton aggregates (Figures 28 and 29). Although it is true that for a given design strength the Edmonton concretes were prepared with a slightly larger cement factor than were any of the Calgary concretes, a careful examination of Figures 28 and 29 or Figure 27 shows that even the Edmonton concrete of 3,000 p.s.i. design (E3) produces a steeper curve and larger mean thermal coefficient than do any of the Calgary concretes of 5,000

MEAN THERMAL COEFFICIENT
V.S.
CEMENT FACTOR

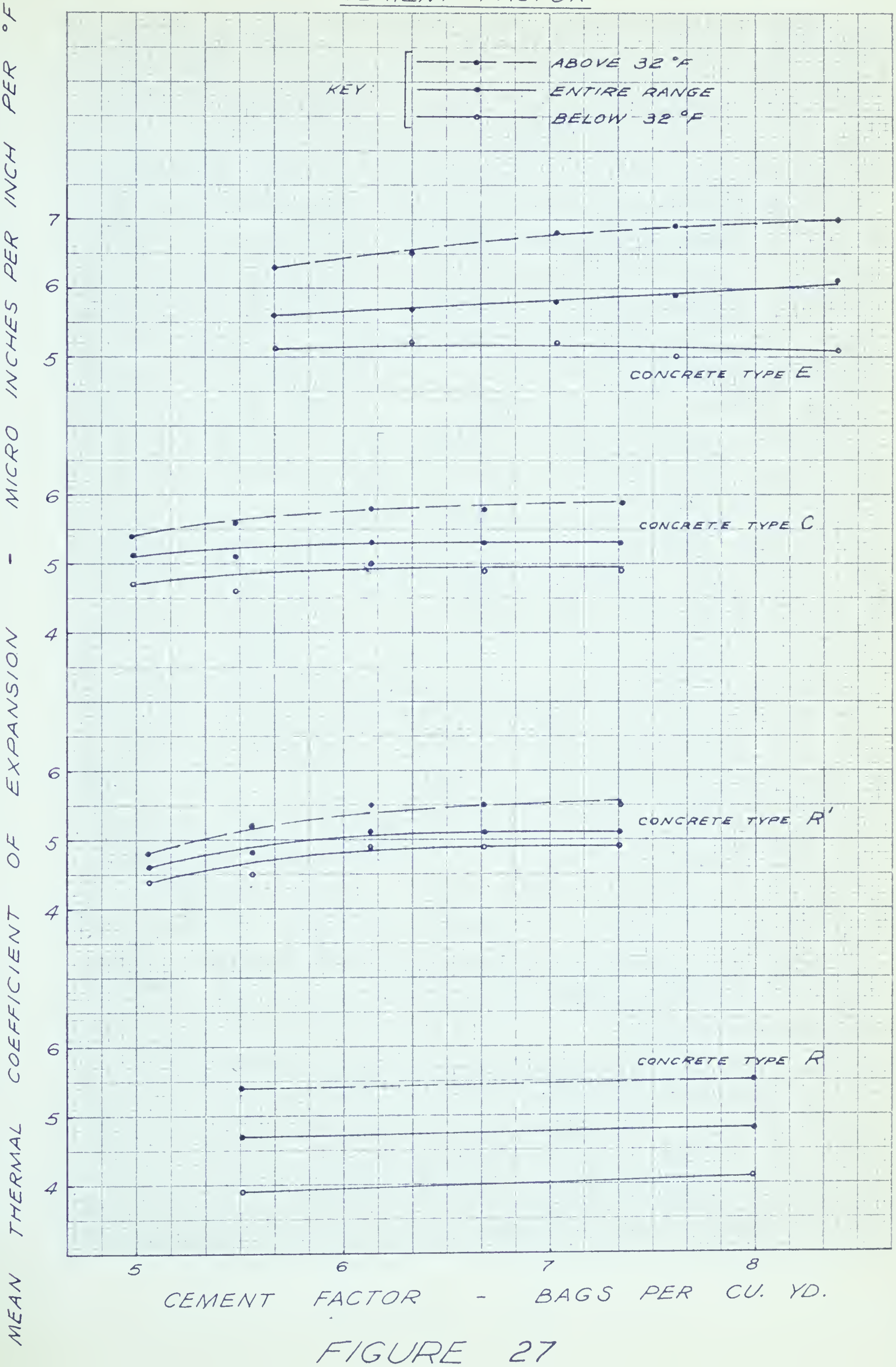


FIGURE 27

COMPARISON OF THERMAL EXPANSION CHARACTERISTICS
— 3000 P.S.I DESIGN STRENGTH

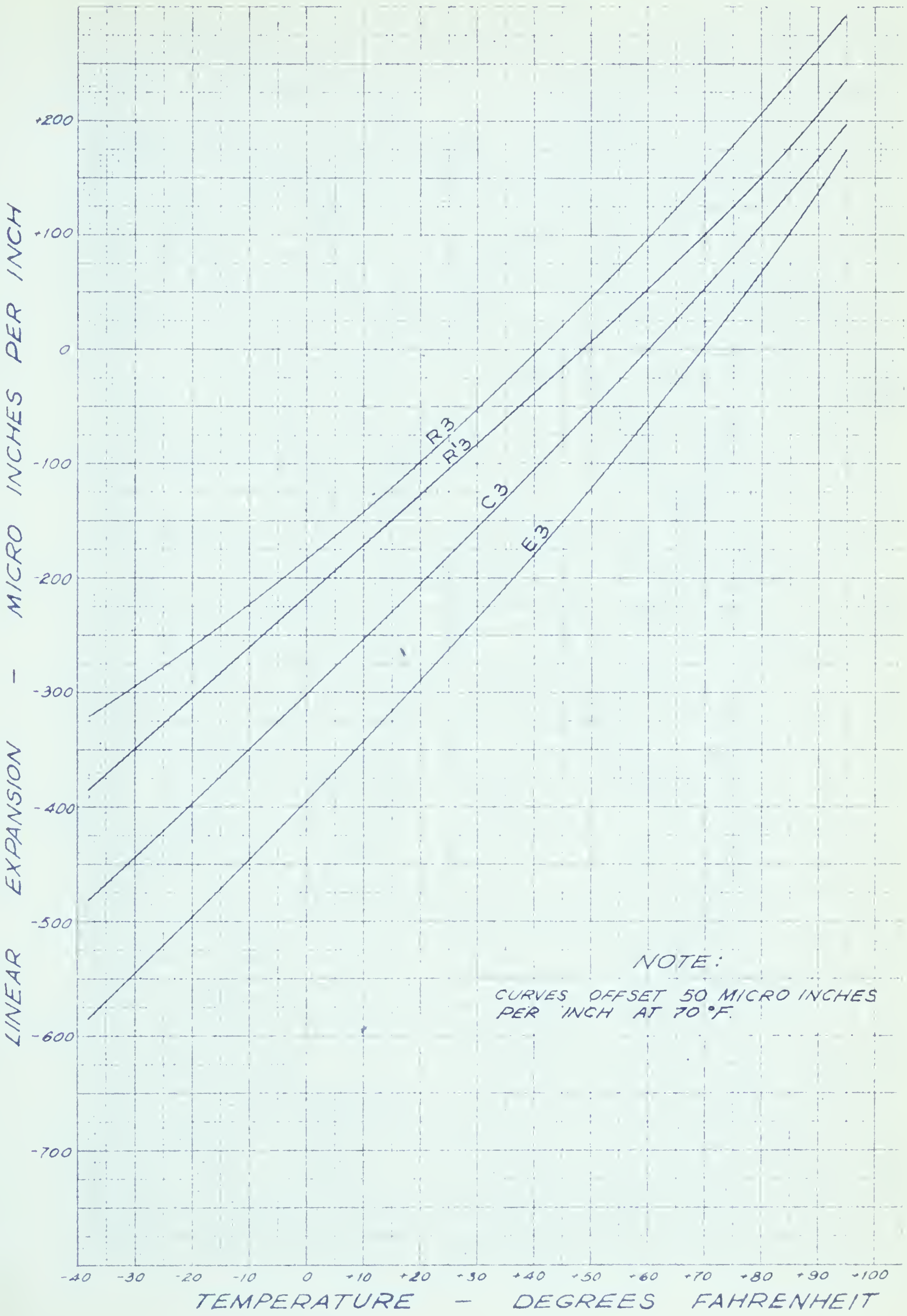


FIGURE 28

COMPARISON OF THERMAL EXPANSION CHARACTERISTICS
— 5000 PSI. DESIGN STRENGTH

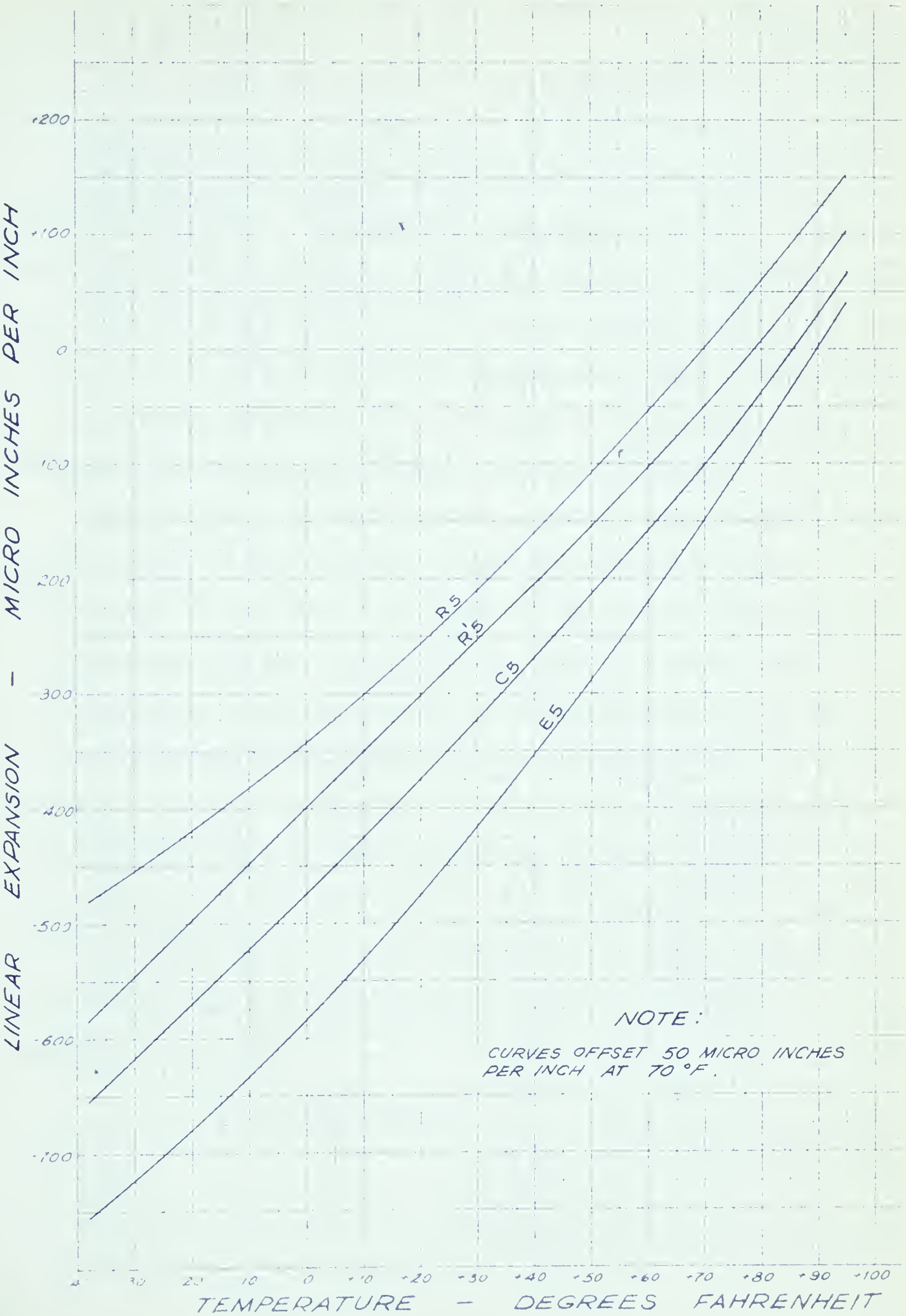


FIGURE 29

p.s.i. design (C5, R'5, R5).

The use of fine aggregate of very low fineness modulus in concrete (type R) does not appear to produce thermal expansion characteristics greatly different from concrete prepared from aggregate of more suitable grading (type R'). Comparison of the thermal expansion properties of these concretes are shown in Figures 27 to 29. Although the curvature of the unit length-temperature relationship is somewhat more pronounced for concrete type R than for type R', the possible difference in the mineralogy of the fine aggregates are probably responsible and not the difference in grading.

A direct comparison of the mean thermal coefficients obtained in the present investigation with coefficients obtained by other investigators does not have a great deal of significance other than to indicate the relative magnitudes. The number of variables which have influenced the magnitude of the thermal coefficient as obtained by each investigation has differed substantially enough that direct comparison can be qualitative only. Figure 30 shows a general comparison of the results of this investigation with the results of some other investigations. It appears from this comparison that the concretes studied in the present program do not possess any highly unusual properties with regard to their coefficients of thermal expansion.

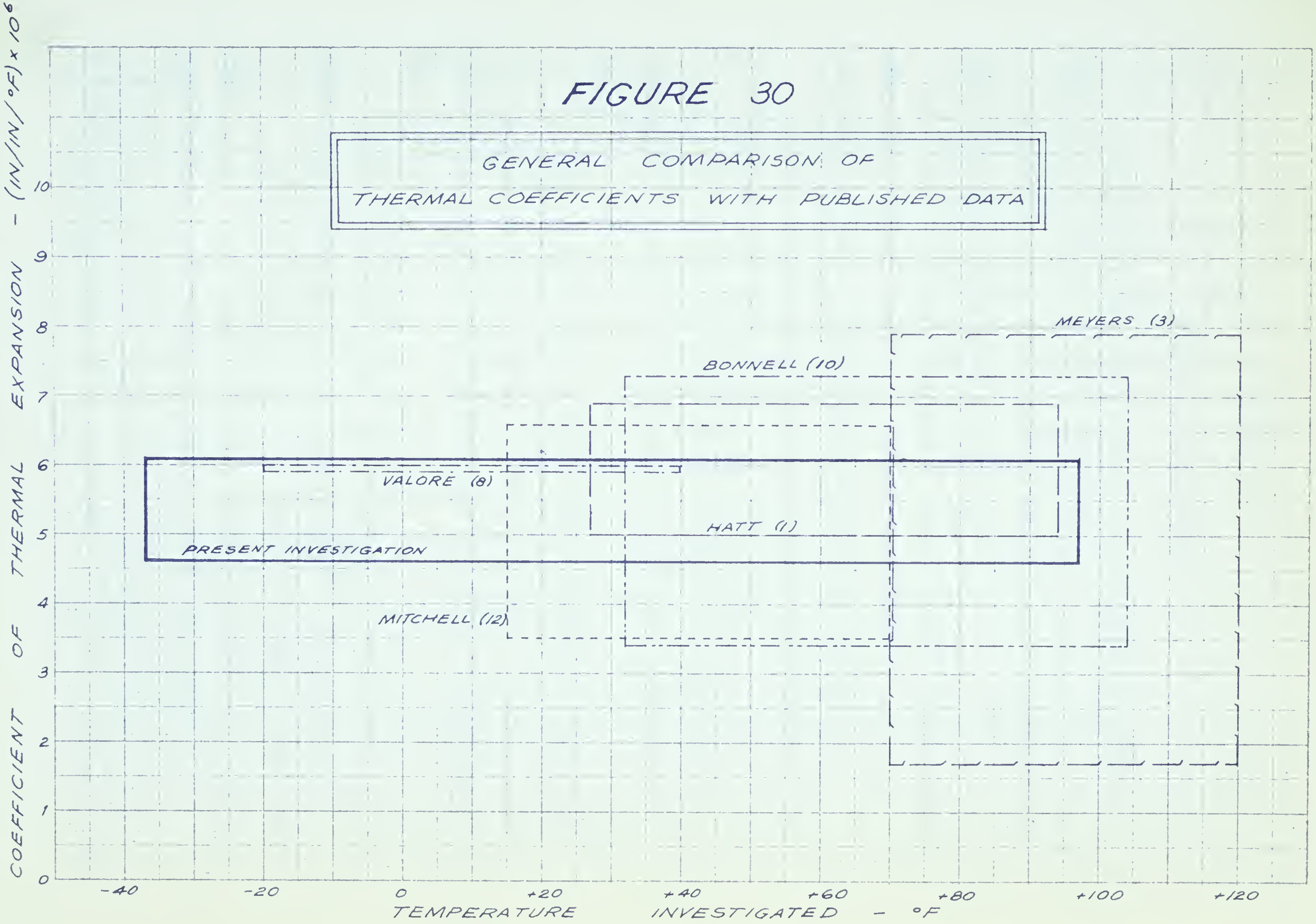


FIGURE 30

GENERAL COMPARISON OF THERMAL COEFFICIENTS WITH PUBLISHED DATA

CHAPTER VII

SUMMARY OF CONCLUSIONS

The principal conclusions which have been formulated in this thesis may be summarized as follows:

1. The concretes which were studied did not possess unusally high or unusually low thermal coefficients.

2. The thermal coefficient was not a constant for the concretes which were studied. Within the limits of the investigation, the instantaneous thermal coefficients increased with temperature.

3. Mean thermal coefficients have been found to range from 4.6 to 6.1 micro-inches per inch per degree Fahrenheit.

4. An increase in cement factor, inherent in an increase in strength, was accompanied by an increase in the mean thermal coefficient.

5. The source of the aggregate had a considerable effect upon the magnitude of the mean thermal coefficient. The Calgary aggregates produced concretes of lower thermal coefficient than the Edmonton aggregates.

6. For the single cycle of freezing and thawing a residual expansion or "permanent set" was evident whenever it was measured.

7. The concretes were in a relatively dry condition and were subjected to a slow thermal expansion test, which produced no sudden discontinuity in the length-temperature relationship upon freezing which would have been the result of the conversion of water to ice within the pore structure of the concrete.

8. The coefficient of thermal expansion for the steel reinforcing bar has been found to be 6.1×10^{-6} inches per inch per degree Fahrenheit.

9. "SR-4" electrical resistance strain gages have proven quite satisfactory in the measurement of length changes due to temperature changes.

CHAPTER VIII

RECOMMENDATIONS

Many instances arose during the development and execution of the tests when it was evident that more suitable procedures might produce better results. Other instances arose when it was realized that further research should be conducted to ascertain the effects of certain variables. A number of recommendations follow for the consideration of anyone desirous of performing further tests of this type.

The first difficulty was encountered in obtaining constant conditions for the accelerated drying process to which all specimens were subjected. A water tank situated against the outside of one of the concrete walls of the "constant" humidity room was responsible for a variable seepage of moisture through the wall and into the room. This situation could be remedied by the introduction of a suitable vapor barrier. In addition, low humidities at room temperature could not be held constant because of the absence of a mechanism capable of introducing or removing small quantities of moisture from the air. Variation in the moisture content from specimen to specimen could be minimized by changes here.

Many improvements which could be made in the temperature control cabinet are obvious. The thermostatic controls were far from adequate and the satisfactory control and maintenance of temperature was achieved only by exhaustive manual control involving a large degree of personal judgment. Excellent mercury thermostats are available or can

be easily fabricated and precisely calibrated but must be used in conjunction with a precision electronic relay, available at some expense. The author would strongly recommend such an investment. Sufficient evidence has been presented in support of the adequacy of "SR-4" electrical resistance strain gages in measuring thermal strains, and if mechanical strain measurements are deleted, a liquid medium which is far superior to air could be used to advantage.

With regard to the thermal expansion of Alberta concretes, further research could be carried out to expand upon the effects of any of the numerous variables.

The field for further research appears to be completely open with regard to the thermal expansion of lightweight concretes.

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APPENDIX I

SAMPLE CALCULATIONS

APPENDIX I

SAMPLE CALCULATIONS

Concrete Mix Design

All concrete mix designs were based upon the recommended practice for selecting proportions for concrete as proposed by A.C.I. Committee 613 (16). Only the units have been changed to conform to Canadian measures.

The calculations performed for concrete type R'5 are presented here to indicate the design procedure used for all concrete types. Detailed explanations of the design procedure are not included since these are to be found elsewhere (16).

Aggregate Origin:	Peerless Rock, Calgary	
Properties:	C. A. Max. Size	1 in.
	C. A. Unit Wt.	101.4 Lb./Cu.Ft.
	C.A. Bulk Sp. Gr.	2.64
	F. A. Bulk Sp. Gr.	2.67
	C. A. Moisture Content	0.12 %
	F. A. Moisture Content	0.10 %
	C. A. Absorption	0.81 %
	F. A. Absorption	1.20 %
	F. A. Fineness Modulus	2.97
Requirements:	28-day strength: 5,000 p.s.i. Slump: 2 to 3 in.	
	Non air entrained.	

Table 5 * : W/C = 3.88 gal. per bag.

Mixing water = 28.5 gal./cu. yd. as determined in trial mix.

Table 3 * : Entrapped air = 1.5%

Cement content required = $\frac{28.5}{3.88}$ = 7.35 bags/cu. yd.

Table 6 * : C.A. Required = .643 x 27 = 17.35 cu. ft.

Solid Volumes per Cubic Yard:

Cement = $\frac{28.5 \times 87.5}{3.15 \times 62.4}$ = 3.27 cu. ft.

C.A. = $\frac{17.35 \times 101.4}{2.64 \times 62.4}$ = 10.70 cu. ft.

Water = $\frac{28.5 \times 10}{62.4}$ = 4.57 cu. ft.

Air = 0.015 x 27 = 0.41 cu. ft.

Sum = 18.95 cu. ft.

F.A = 27 - 18.95 = 8.05 cu. ft.

Weights per Cubic Yard (dry):

Cement = 7.35 x 87.5 = 643 Lbs.

C.A. = 17.35 x 101.4 = 1760 Lbs.

Water = 28.5 x 10 = 285 Lbs.

F.A.= 8.05 x 166.5 = 1340 Lbs.

* A. C. I. Tables

Table 27

Mix Proportion Corrections for One Cu. Ft. Mix
Concrete Type R'5

	Cement	C. A.	F. A.	Water
Dry Weight Lbs.	23.8	65.2	49.6	10.56
Moisture Content %		.12	.10	
Absorption %		.81	1.20	
Water Correction %		+.69	+1.1	
Water Correction Lbs.		+.45	+.55	+1.00
Aggregate Correction (Moisture Content x Dry Weight)		.08	.06	
Net Weight Lbs.	23.8	65.3	49.6	11.56

The required weight of coarse aggregate was obtained by recombining the size fractions according to the natural grading which was shown in Table 2. The recombination proportions for the one cubic foot mix were as follows:

Screen Size:	3/4	1/2	3/8	No. 4	Pan
Percent Retained:	23.4	47.0	13.6	16.0	0.0
Weight (Lbs.):	15.3	30.7	8.9	10.4	0.0

Total Weight = 65.3 Lbs.

Reduction of "SR-4" Strain Gage Data

The method by which the reduced data were obtained for the "SR-4" strain gage readings as shown in Tables 8 to 25, inclusive, is described in the following sample calculations as applied to concrete type R'5.

A copy of the original readings for concrete type R'5, Specimen 1, is shown in Table 28 and the corresponding readings which were taken to check for drift in the strain indicator are shown in Table 29. Calculations were performed in tabular form as shown in Table 30. Table 22 which shows the reduced data for concrete type R' is repeated here for convenient reference.

The first reduction made, was with regard to temperature. The two specimen and the two dummy temperature readings were averaged separately and the average readings corrected according to the thermocouple calibration curves shown in Figures 36, 37 and 38 of Appendix III. Consider reading 1, Table 28, for example:

Mean specimen temperature: $(-35.8 -35.8) \div 2 = 35.8$

Corrected (Figure 36): $- 36.9^{o}F$

Mean dummy temperature: $(-35.8 -35.8) \div 2 = 35.8$

Corrected (Figure 36): $- 36.9^{o}F$

The remaining temperatures shown in Table 30 were obtained similarly.

The next step was to obtain the mean strain gage reading. Consider reading 1, Table 28 again:

$$(11894 + 10423 + 12825 + 10904) \div 4 = 11511$$

The fourth column of Table 30 was arrived at in this manner.

Table 28

Temperature - SR-4 Strain Gage Readings   Concrete Type R'5   Specimen 1

Read. No.	Date	Time	Temperature °F			SR-4 Strain Gage Reading			
			Air	Specimen	Dummy	1	2	3	4
1.	Jan. 22	1:42 PM	-35.7	-35.8	-35.8	11894	10423	12825	10904
			-35.8	-35.8					
2.	Jan. 22	5:25 PM	- 5.4	- 5.4	- 5.4	11690	10248	12638	10714
			- 5.4	- 5.4	- 5.4				
3.	Jan. 23	12:10 PM	+19.3	+19.0	+18.9	11523	10103	12481	10553
			+19.2	+19.0	+19.0				
4.	Jan. 23	3:49 PM	+42.0	+42.1	+42.1	11347	9941	12313	10381
			+42.1	+42.1	+42.0				
5.	Jan. 24	12:30 PM	+72.1	+71.8	+72.1	11136	9753	12111	10180
			+72.1	+71.8	+72.1				
6.	Jan. 24	4:40 PM	+98.0	+97.6	+97.6	10978	9607	11943	10022
			+98.1	+97.6	+97.6				

Table 29

Check for Instrument Zero Drift
During Test on Concrete Type R'5

Active Gage		A	C	B	D	Mean Zero Drift
Dummy Gage		C	A	D	B	
Date	Time					
Jan. 22	1:39 PM	10792	11177	10209	11758	0
	1:47 PM	10791	11177	10209	11758	0
	5:17 PM	10792	11177	10209	11760	0
	5:45 PM	10792	11175	10209	11758	0
Jan. 23	12:07 PM	10792	11176	10209	11759	0
	12:21 PM	10792	11178	10209	11761	+1
	3:48 PM	10792	11178	10209	11760	+1
	3:55 PM	10793	11174	10209	11758	0
Jan. 24	12:20 PM	10791	11175	10209	11759	0
	12:37 PM	10790	11175	10207	11758	-1
	4:25 PM	10789	11175	10208	11757	-2
	5:01 PM	10790	11176	10208	11759	-1

Table 22 REDUCED THERMAL EXPANSION DATA CONCRETE TYPE R'5

TIME+ HRS.	SPECIMEN 1		SPECIMEN 2		SPECIMEN 3		MEAN	
	TEMP.* °F	δL/L × 10⁶‡	TEMP.* °F	δL/L × 10⁶‡	TEMP.* °F	δL/L × 10⁶‡	TEMP.* °F	δL/L × 10⁶‡
REDUCED SR-4 STRAIN GAGE READINGS								
0	- 36.9	- 549	- 36.8	- 534	- 36.8	- 513	- 36.8	- 532
4	- 8.0	- 406	- 8.3	- 399	- 8.0	- 377	- 8.1	- 394
23	+ 16.9	- 270	+ 17.0	- 268	+ 17.2	- 254	+ 17.0	- 264
27	+ 40.4	- 157	+ 40.3	- 160	+ 40.4	- 150	+ 40.4	- 156
47	+ 70.4	+ 4	+ 70.4	+ 5	+ 70.4	+ 7	+ 70.4	+ 5
51	+ 97.1	+ 171	+ 97.2	+ 170	+ 97.7	+ 175	+ 97.3	+ 172
REDUCED DEMEC STRAIN GAGE READINGS								
0	- 36.9	- 538	- 36.8	- 547	- 36.0	- 546	- 36.6	- 544
4	- 8.0	- 399	- 8.0	- 404	- 8.0	- 398	- 8.0	- 400
23	+ 16.4	- 266	+ 16.9	- 271	+ 17.1	- 267	+ 16.8	- 268
27	+ 40.4	- 161	+ 40.4	- 161	+ 40.6	- 159	+ 40.5	- 160
47	+ 70.5	+ 3	+ 70.5	+ 3	+ 70.6	+ 3	+ 70.5	+ 3
51	+ 97.2	+ 165	+ 97.2	+ 180	+ 97.5	+ 165	+ 97.3	+ 170

+ Time from start of test. * Mean of two thermocouples. ‡ Datum at 70 °F.

The correction to be applied to account for drift in the strain indicator was obtained by considering the drift in instrument zero with respect to the readings taken at the start of a particular test run. The calculation did not necessitate the establishment of instrument zero itself, although the results are the same. Consider the reading at 5:01 p.m., January 25th, Table 29, for example:

Initial readings:	10792	11177	10209	11758
5:01 p.m. readings:	10790	11176	10208	11759
Net change in readings:	-2	-1	-1	+1
Net change in instrument zero:	$(-2 -1) \div 2$		$(-1 +1) \div 2$	

Mean change in instrument zero or "zero drift":

$$\frac{\left[(-2 -1) \div 2\right] + \left[(-1 +1) \div 2\right]}{2} = -0.75$$

All values in the last column of Table 29 were obtained in this manner and rounded to the nearest micro-inch per inch favoring zero. The mean strain gage readings were corrected accordingly, to the nearest micro-inch per inch. Consider reading 6, Table 30:

Mean strain gage reading: 10637

Time read: 4:40 P.M.

Mean zero drift interpolated according to time:

$$-1 + \left[\frac{(5{:}01 - 4{:}40)}{(5{:}01 - 4{:}25)} \times (-2 - -1)\right] = -2$$

Corrected mean strain reading: $10637 - 2 = 10635$

The values in the fifth column of Table 30 were obtained similarly.

In order to establish a reference datum at 70°F for the unit length changes, the mean corrected strain reading corresponding to 70°F was obtained by interpolation between readings 4 and 5 as follows:

$$10996 - \left\{\left[(70 - 40.4) \div (70.4 - 40.4)\right] \times (10996 - 10795)\right\} = 10798$$

The indicated unit length increase, Table 30, Column 6, was obtained by considering the above reading as datum. These length changes represent differences in unit length between the specimen and comparator or dummy, with the unit length at 70°F taken as datum. Consider reading 6 for example:

Indicated unit length increase: $(10635 - 10798) = 163$

The unit length increase of the dummy or comparator was obtained by linear interpolation of the data given by the U.S. National Bureau of Standards, as recorded in Chapter IV and repeated in Table 31 in converted form. Consider reading 1, Table 30:

Unit length of comparator at -36.9°F:

$$\left\{\left[(1070 - 1410) \div 30\right] \times \left[(36.9 - 20.0)\right]\right\} - 1070 = 1262$$

Table 30

SR-4 Calculation Sheet			Concrete Type R'5				Specimen 1
	Corrected Temperature		Mean Strain		Per Datum at 70°F		
Read. No.	Specimen °F	Dummy °F	As Read	Corrected For Zero Drift	Indicated Unit Length Increase	Unit Length Increase of Dummy	Net Unit Length Increase
			Micro-inches per Inch				
1	-36.9	-36.9	11511	11511	+713	-1262	-549
2	- 8.0	- 8.0	11322	11322	+524	- 930	-406
3	+16.9	+16.9	11165	11165	+367	-637	-270
4	+40.4	+40.4	10995	10996	+198	-355	-157
	70	70		10798	0	0	0
5	+70.4	+70.6	10795	10795	- 3	+ 7	+ 4
6	+97.1	+97.1	10637	10635	-163	+334	+171

Table 31

Thermal Expansion Characteristics of Aluminum Comparator

Temperature (°F)	Unit Linear Thermal Expansion (Micro-inches per Inch)
- 50	-1410
- 20	-1070
+ 10	- 720
+ 40	- 360
+ 70	0
+100	+ 370
+130	+ 750

The last column in Table 30 was obtained by adding the sixth and seventh columns algebraically.

The second and last columns of Table 30 were recorded in Table 22 as the Reduced SR-4 Strain Gage Readings. The calculations were similar for the other two specimens and the readings for the three specimens were averaged and recorded in the last two columns of Table 22. The times given in the first column of Table 22, are the mean for the three specimens and have been rounded to the nearest hour. These were recorded to give some indication of the rate at which each particular test was performed.

All except the most trivial calculations were made with the aid of a computing machine. The results were stored on tape and thoroughly checked.

Reduction of "Demec" Gage Data

The following sample calculations, as applied to concrete type R'5, show the method by which the reduced data were obtained for the "Demec" strain gage readings as shown in Tables 8 to 25 inclusive.

A copy of the original readings for concrete type R'5, specimen 1, is shown in Table 32, and the calculations which were performed are shown in Table 33 in tabular form. The reduced data for concrete type R' (Table 22) has been repeated in the preceding section for convenient reference.

The first reduction made here, as with the "SR-4" readings, was with regard to temperature. Readings A and B, Table 32, were averaged and corrected in the same way as for the "SR-4" readings to obtain the second column of Table 33. Reading C which was a measure of the temperature under the insulation was ignored. This procedure had very little effect, if any, upon the validity of the results in view of the temperature distribution through the specimen as described in Appendix III.

As pointed out in Chapter IV, each specimen was taken out of the temperature control cabinet just prior to taking the "Demec" gage readings. In most instances a small change in length of the specimens was observed by repeating the reading at the first gage point (see Table 32). In order to correct for this change which would be due to a small indeterminable temperature rise (drop) of the specimen, it was assumed that the increase (decrease) in temperature varied linearly with time and that the readings from gage point to gage point were taken at uniform intervals of time. These assumptions are

Table 32

Temperature-Demec Gage Readings   Concrete Type R'5   Specimen 1

Read No.	Date	Time	Temperature °F			Demec Gage Reading			
			A	B	C	1	2	3	4
1	Jan. 22	1:57 PM	-35.8	-35.8	-35.7	767.5 768.1	763.6	764.1	766.4
2	Jan. 22	5:54 PM	- 5.4	- 5.4	- 5.4	781.0 781.2	778.0	778.0	781.0
3	Jan. 23	12:26 PM	+18.5	+18.5	+18.5	793.6 793.5	791.5	792.4	794.5
4	Jan. 23	4:08 PM	+42.0	+42.0	+42.0	803.6 803.8	802.6	803.6	805.2
5	Jan. 24	12:47 PM	+72.0	+72.0	+72.5	820.0 819.9	819.0	820.6	821.9
6	Jan. 24	5:07 PM	+97.7	+97.7	+98.2	835.5 835.3	835.5	838.0	838.3

Remarks: 1. Gage was checked to standard bar of 800.0 before and after each set of readings.

2. Temperature: A and B = specimen, C = under insulation.

Table 33

Demec Calculation Sheet — Concrete Type R'5 — Specimen 1

Read. No.	Corrected Temp. °F	Mean Reading	Difference In Mean Reading	Difference x 9.8	Unit Length Increase
				Micro-inches per Inch	
1	-36.9	765.2			-538
			-14.2	-139	
2	- 8.0	779.4			-399
			-13.6	-133	
3	+16.4	793.0			-266
			-10.7	-105	
4	+40.4	803.7			-161
			-16.4	-161	
	+70.0	820.1			0
			+ 0.3	+ 3	
5	+70.5	820.4			+ 3
			+16.5	+162	
6	+97.2	836.9			+165

approximately correct and are certainly better than none. The corrections made in this manner were small and it is to be emphasized that the net effect of error in the assumptions can be considered negligible. Consider reading 1, Table 32, to illustrate the application of the foregoing assumptions in arriving at the mean corrected "Demec" gage reading:

Net increase in first reading: (768.1 - 767.5) = 0.6

Considering the first reading on gage point 1 to have had no error due to temperature rise:

Error in reading: 1 = 0

2 = (0.6) ÷ 4 x 1 = 0.15

3 = (0.6) ÷ 4 x 2 = 0.30

4 = (0.6) ÷ 4 x 3 = 0.45

Or error in sum of 4 readings: 1.5 x 0.6 = 0.9

Corrected mean:

(767.5 + 763.6 + 764.1 + 766.4 - 0.9) ÷ 4 = 765.2

The procedure described was performed to obtain all readings in the second column shown in Table 33 with the exception of reading 3. The decrease in the reading for gage point 1 obviously could not have been the result of a temperature drop and is apparently due to personal or instrumental error. Cases such as this were not numerous, and a direct mean of the first four readings was utilized.

The difference between successive mean readings was obtained next to form the fourth column in Table 33, and multiplication of each of these terms by the "Demec" gage factor of 9.8 converted the differences to micro-inches per inch as may be seen in the fifth column. The unit

length increase based upon a datum unit length at 70° F was obtained by the summation of the differences and is recorded in the sixth column of Table 33.

The second and last columns of Table 33 were recorded in Table 22 as the Reduced Demec Strain Gage Readings. The remaining entries in Table 22 follow the same logic as discussed for the Reduced SR-4 Strain Gage Readings in the preceding section.

APPENDIX II

PROOF TESTS

APPENDIX II

PROOF TESTS

In order to establish conclusively that the application of "SR-4" strain gages in measuring the thermal expansion of concrete would give satisfactory results, samples of materials of predetermined thermal expansion characteristics were obtained from two sources and tested. The first of these was a commercial sample of vitreous silica glass. The United States National Bureau of Standards presented the following data as being typical and very close to the actual expansion of such material:

Temperature (°F)	Linear Thermal Expansion (%)
-50	-0.0017
-20	-0.0015
+10	-0.0011
+40	-0.0006
+70	0.0000
+100	+0.0014

The linear thermal expansion, as given above was converted to micro-inches per inch and plotted in Figure 31.

The second sample of predetermined thermal expansion characteristics was provided by the United States Steel Export Company along with the following thermal expansion data which had been determined at their Applied Research Laboratory:

Temperature (°F)	Linear Thermal Expansion (%)
− 50	− 0.078
− 25	− 0.062
0	− 0.045
+ 50	− 0.012
+ 70	0.000
+100	+ 0.017

The linear thermal expansion was converted to micro-inches per inch and plotted in Figure 32.

Tables 34 and 35 show the reduced data which were obtained for these samples using procedure and methods similar to those used for the concrete specimens. "Demec" gage data were not obtained for the U.S.S. steel sample since sufficient evidence of the use of the "Demec" gage was obtained in the test on the vitreous silica sample.

Comparisons of the data which were obtained are shown in Figures 31 and 32. Agreement is very good for the vitreous silica sample. Agreement is not as good for the U.S.S. steel sample but agreement of results obtained by the two completely separate test runs is excellent.

THERMAL EXPANSION OF VITREOUS SILICA GLASS

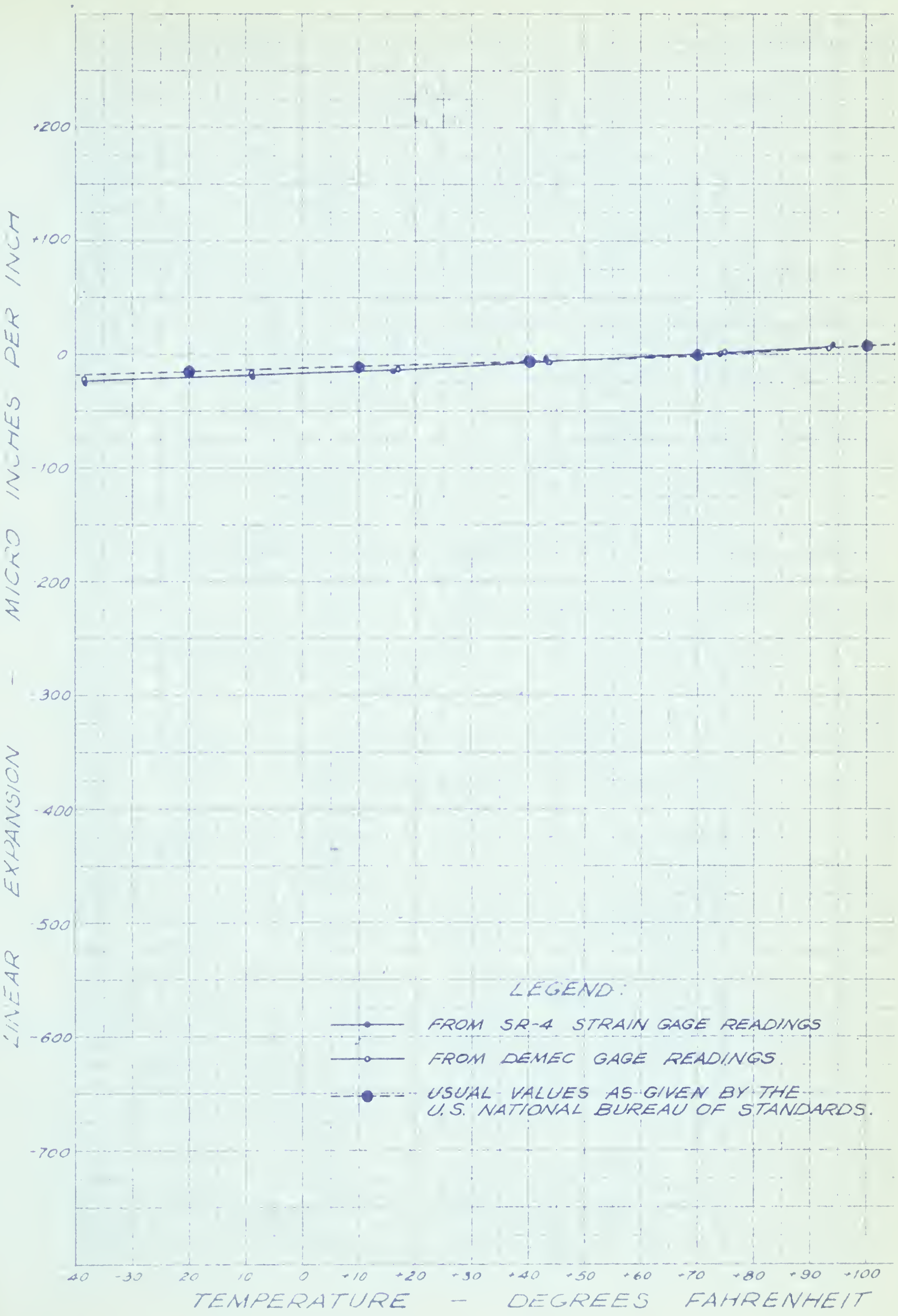


FIGURE 31

THERMAL EXPANSION OF U.S.S. STEEL SAMPLE

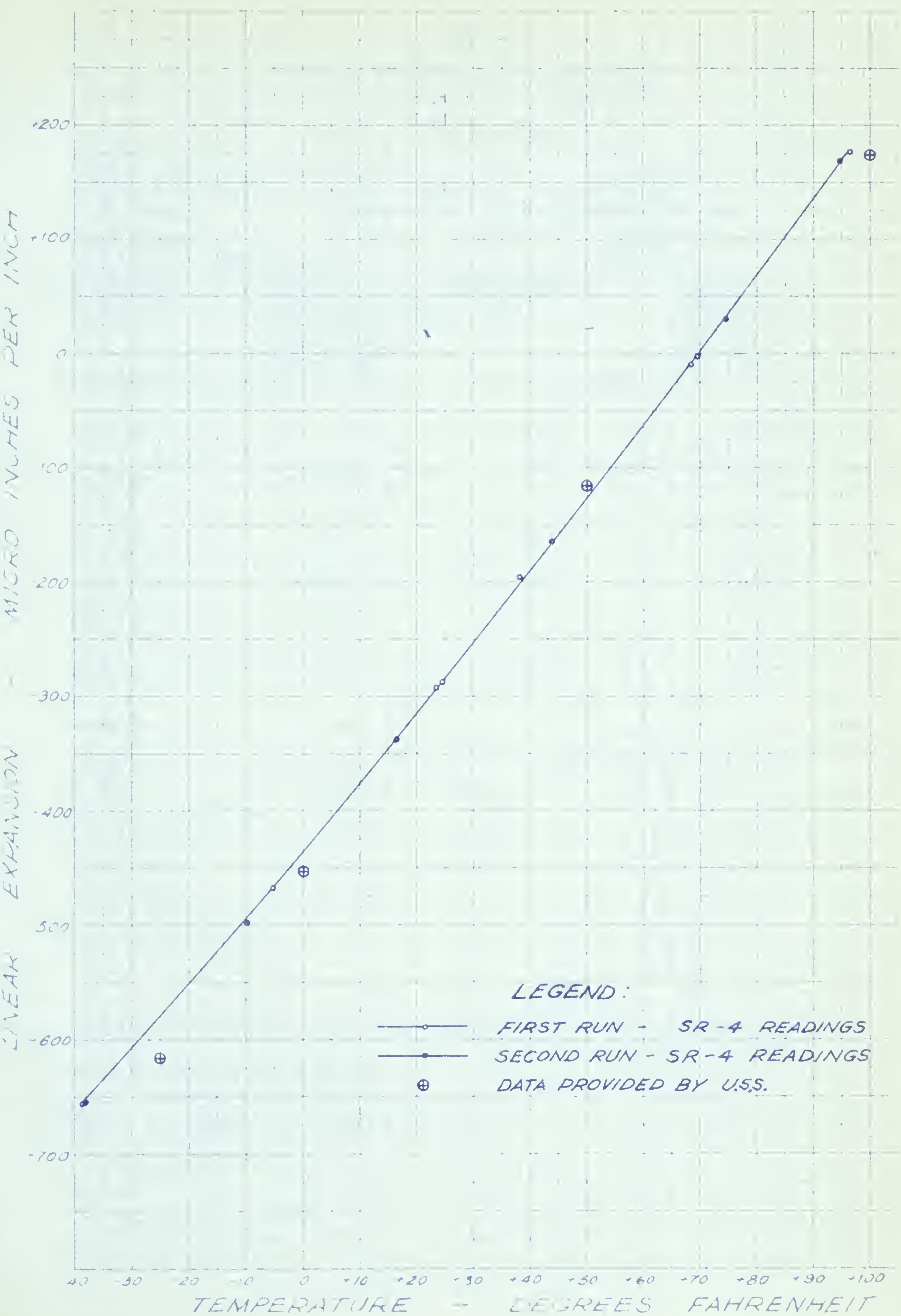


FIGURE 32

Table 34

Reduced Thermal Expansion Data

- U.S.S. Steel

SR-4 Strain Gage Readings

Run 1		Run 2	
Temperature * °F	Mean † Expansion (Micro-inches per Inch)	Temperature * °F	Mean † Expansion (Micro-inches per Inch
+ 69.7	- 3	- 38.4	- 657
- 38.4	- 657	- 10.0	- 498
+ 5.1	- 468	+ 16.3	- 339
+ 23.6	- 292	+ 43.9	- 165
+ 24.2	- 287	+ 74.5	+ 30
+ 38.1	- 196	+ 94.4	+ 168
+ 68.3	- 10		
+ 96.3	+ 177		

* Mean of two thermocouples.

† Datum at 70°F.

Table 35

Reduced Thermal Expansion Readings

- Vitreous Silica Glass

Temperature * °F	Mean ≁ Expansion (Micro-inches per Inch)
Reduced SR-4 Strain Gage Readings:	
- 38.4	- 26
- 9.8	- 22
+ 16.4	- 15
+ 43.1	- 3
+ 74.5	+ 1
+ 94.0	+ 9
Reduced Demec Strain Gage Readings:	
- 38.5	- 23
- 9.0	- 18
+ 16.9	- 14
+ 43.9	- 7
+ 74.9	+ 1
+ 93.3	+ 5

* Mean of two thermocouples.

≁ Datum at 70°F.

APPENDIX III

PRELIMINARY TESTS

APPENDIX III

PRELIMINARY TESTS

Establishment of Test Methods

In order to establish basic techniques and procedures, a preliminary thermal expansion test was performed on a small concrete beam 3-1/2" x 4-1/2" x 18" in the laboratory using the crudest of apparatus. Six "SR-4" strain gages of 1" gage length and six "Demec" gage points were mounted on the specimen. The circuit for the "SR-4" strain gages was the same as shown previously in Figure 4, except in simplified form. A brass rod of roughly known thermal coefficient (10.8 micro-inches per inch per degree Fahrenheit) on which only one "SR-4" strain gage was mounted was used as comparator. A layer of heavy building paper was used as insulation to help damp out the effects of temperature fluctuations. The specimen was set horizontally within a small refrigeration unit. Temperatures were measured by means of a thermometer, placed under the insulation.

The results of the test are shown graphically in Figure 33 with the zero length change datum taken at +79° F. Most of the test methods and procedures were based upon the observations and experiences gained in this test.

Selection of Insulation

Some form of insulation for the test specimens was considered necessary in order to provide a damping effect on temperature fluctuations within the temperature control cabinet and to prevent undue rise

THERMAL EXPANSION OF PRELIMINARY CONCRETE SPECIMEN

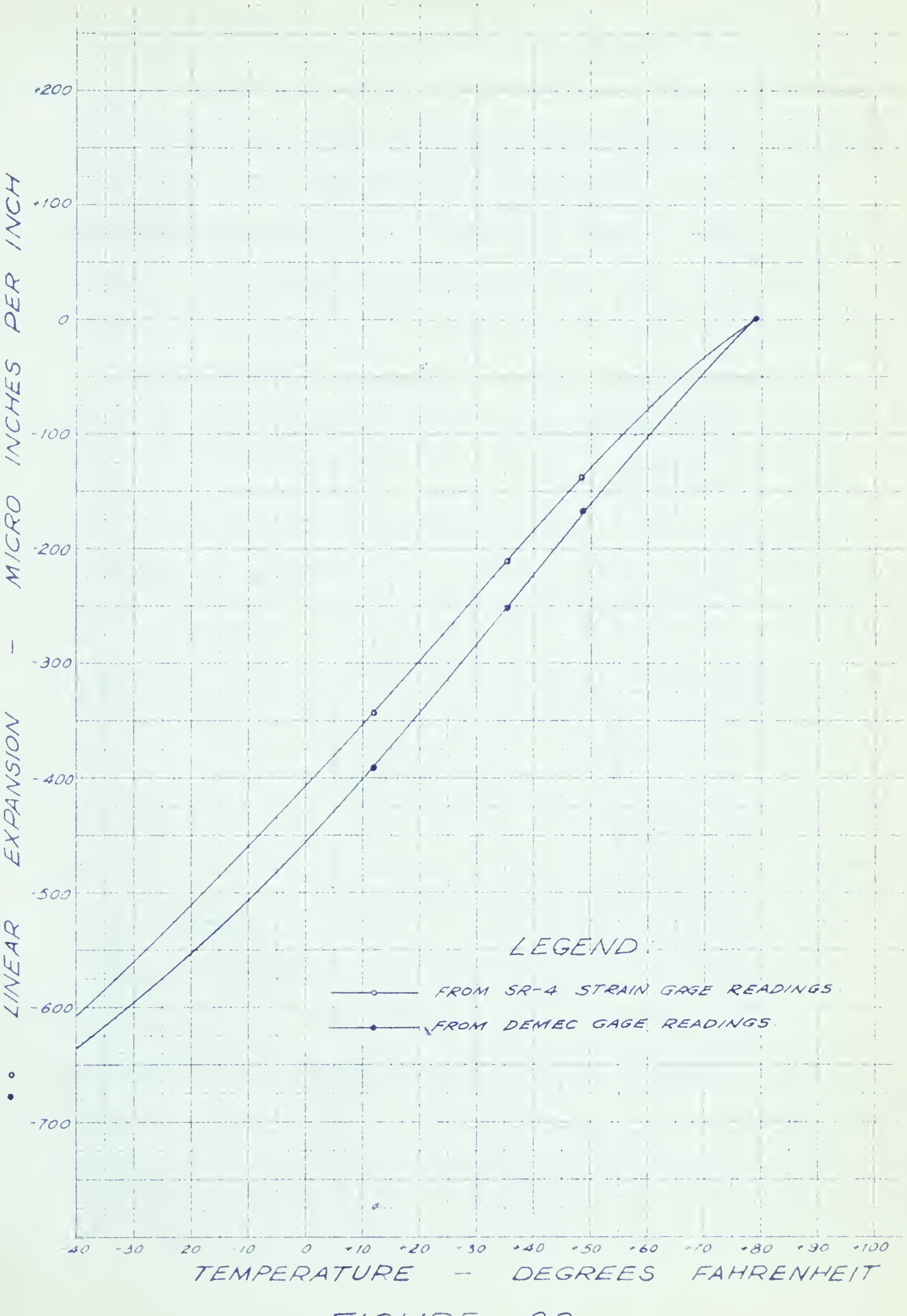


FIGURE 33

in the temperature of the specimens when removed from the cabinet for "Demec" gage readings. A suitable form of insulation would be thin to allow the "Demec" gage points to protrude, strong and durable enough to withstand repeated handling of the specimens, easily applied, and possess good insulating qualities. Three types of insulating material which appeared to be suitable were procured; namely, a heavy felt cloth, a thin quilted cloth material, and a thin foam plastic material.

In order to obtain some measure of the relative insulating qualities of these materials, a test was conducted on three 3-1/2" diameter by 10" concrete cylinders, each insulated with one of the materials. The specimens were placed in a small refrigeration unit and brought to a temperature of about $0^{\circ}C$ at which they were held for about 24 hours. This particular temperature was chosen since it was compatible with the lower temperature limit of a readily available thermometer which was graduated in $0.1^{\circ}C$ divisions. The specimens were removed from the refrigeration unit one at a time, the thermometer was placed under the insulation, and temperature and time readings were observed and recorded as shown in Table 36. The data are shown graphically in Figure 34. The relative insulating properties were compared by observing the time required for the temperature under the insulation to rise $0.1^{\circ}C$ from the minimum temperature reading. The small arrows in Figure 34 indicate these conditions.

Table 36

Temperature - Time Data for Various Insulating Materials

Felt			Foam Plastic			Quilting		
Temp.	Time		Temp.	Time		Temp.	Time	
	Min.	Sec.		Min.	Sec.		Min.	Sec.
-0.9	0	00	-0.2	0	00	-2.1	0	00
-1.0		15	-0.4		35	-2.5		25
-1.0		40	-0.5	1	17	-3.0	1	00
-1.1	1	05	-0.6		43	-3.2		36
-1.1		20	-0.6	2	00	-3.3	2	20
-1.1		55	-0.6		15	-3.3		40
-1.1	2	10	-0.6		30	-3.3		55
-1.1		20	-0.6		50	-3.2	3	30
-1.0		35	-0.6	3	00	-3.1		58
-1.0		50	-0.5		17	-3.0	4	30
-1.0	3	35	-0.3	4	30	-2.9	5	25
-0.9		58	-0.2	5	45	-2.8		55
-0.8	4	55	+0.3	7	27	-2.5	7	18
-0.7	5	30	+0.4	7	56	-2.0	8	35
-0.2	8	45	+0.5	8	20	-1.9	9	00
-0.1	9	20						

The curves indicated that the quilting was inferior but that there was little difference in the insulating properties of the felt and foam plastic. The felt was chosen because of its slightly superior handling properties.

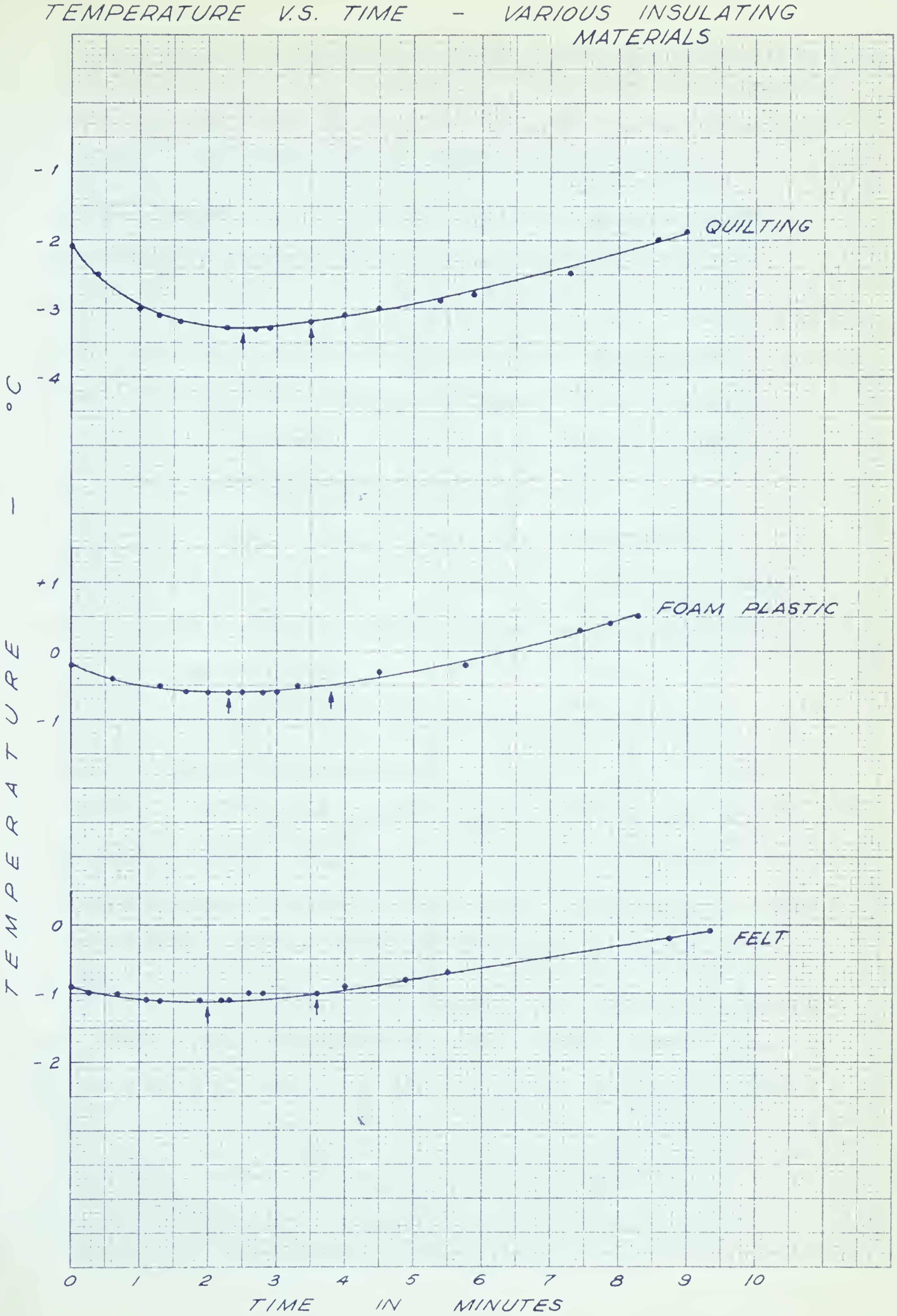

TEMPERATURE V.S. TIME - VARIOUS INSULATING MATERIALS
QUILTING
FOAM PLASTIC
FELT
TEMPERATURE - °C
-1
-2
-3
-4
+1
0
-1
0
-1
-2
0
1
2
3
4
5
6
7
8
9
10
TIME IN MINUTES

FIGURE 34

After the temperature control cabinet had been assembled, a test was run to establish the effectiveness of the felt insulation in damping the effects (on the specimens) of temperature fluctuations within the cabinet. A 3-1/2" diameter by 10", concrete specimen insulated with two layers of felt was placed within the cabinet and left for several hours. Temperature readings were taken at several points within the specimen by means of thermocouples which were inserted into holes, the locations of which are shown in Figure 35a. In this way, the temperature distribution through the specimen was measured while the cabinet temperature fluctuated.

At a later time, the specimen was brought to equilibrium with the cabinet and then the cabinet temperature was purposely increased several degrees in order to establish the nature of the temperature gradient through the specimen.

The data obtained in these tests are shown in Table 37 and are represented graphically in Figure 35.

The results indicated that the damping effects of the felt insulation were adequate (Figure 35b) and that two thermocouples, one at the center and one located half way between the center and outside of the specimen, would be sufficient for temperature measurements of all specimens. Even when the temperature of the surroundings was much different than the temperature of the specimen (Figure 35c), the temperature was uniform ($\pm 0.1^{o}F$) throughout the specimen except at the surface. The effect of a thin layer at the surface being at a temperature different than the rest of the specimen would be negligible in the results of thermal expansion tests run under good

Table 37

Temperature Variation Through Concrete Specimen

Time (Hrs.:Min.)	Elapsed Time (Min.)	Temperature - °F					
		1	2	3	4	5	6
10:37	0	-36.3	-36.3	-36.3	-36.3	-36.3	-36.3
10:41	4	-36.5	-36.5	-36.5	-36.5	-36.5	-36.5
10:45	8	-36.5	-36.5	-36.5	-36.5	-36.5	-36.3
10:49	12	-36.4	-36.4	-36.4	-36.4	-36.4	-35.0
10:53	16	-36.3	-36.4	-36.3	-36.4	-36.4	-32.9
10:57	20	-36.4	-36.4	-36.4	-36.4	-36.3	-36.0
11:01	24	-36.4	-36.4	-36.4	-36.4	-36.4	-36.8
11:05	28	-36.4	-36.4	-36.4	-36.4	-36.4	-36.5
4:31	0	+15.6	+15.6	+15.5	+15.5	+15.5	+23.1
4:35	4	+15.6	+15.5	+15.5	+15.5	+16.8	+23.3
4:39	8	+16.3	+16.2	+16.2	+16.2	+17.4	+22.2
4:43	12	+17.1	+17.1	+17.1	+17.1	+18.1	+22.8
4:47	16	+17.8	+17.7	+17.7	+17.7	+18.6	+23.3

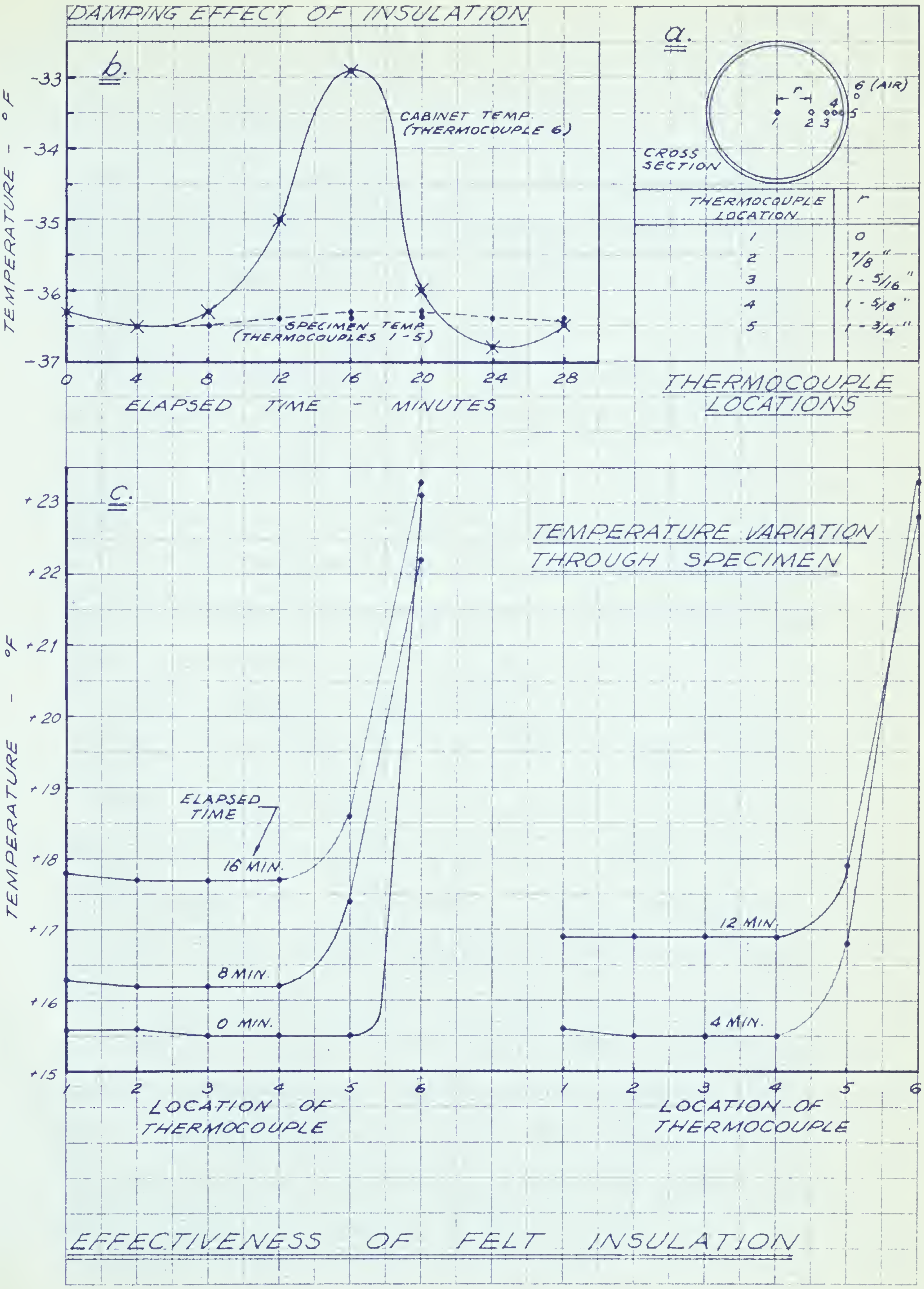

DAMPING EFFECT OF INSULATION
b.
CABINET TEMP. (THERMOCOUPLE 6)
SPECIMEN TEMP. (THERMOCOUPLES 1 - 5)
TEMPERATURE - °F
-33
-34
-35
-36
-37
0
4
8
12
16
20
24
28
ELAPSED TIME - MINUTES
a.
6 (AIR)
r
1
2
3
4
5
CROSS SECTION
THERMOCOUPLE LOCATION
r
1 0
2 7/8"
3 1 - 5/16"
4 1 - 5/8"
5 1 - 3/4"
THERMOCOUPLE LOCATIONS
c.
TEMPERATURE VARIATION THROUGH SPECIMEN
TEMPERATURE - °F
+23
+22
+21
+20
+19
+18
+17
+16
+15
ELAPSED TIME
16 MIN.
8 MIN.
0 MIN.
12 MIN.
4 MIN.
1
2
3
4
5
6
LOCATION OF THERMOCOUPLE
LOCATION OF THERMOCOUPLE
EFFECTIVENESS OF FELT INSULATION

FIGURE 35

temperature equilibrium conditions.

Thermocouple Calibration

The necessity of calibration became evident when a check was made on the correctness of the thermocouple temperatures, as read on the "Brown Electronik" potentiometer and recorder, in a freezing mixture of ice and water.

The thermocouples were calibrated against the best thermometer which was readily available. The thermometer was an "A.S.T.M. 33C Aniline Point" partial immersion thermometer of -38°C to +42°C temperature range with 0.2°C graduations. This thermometer was checked against another thermometer (total immersion "Cenco 5903048" of -10°C to +50°C range and 0.1°C graduations) at several temperatures and was in agreement as nearly as could be read.

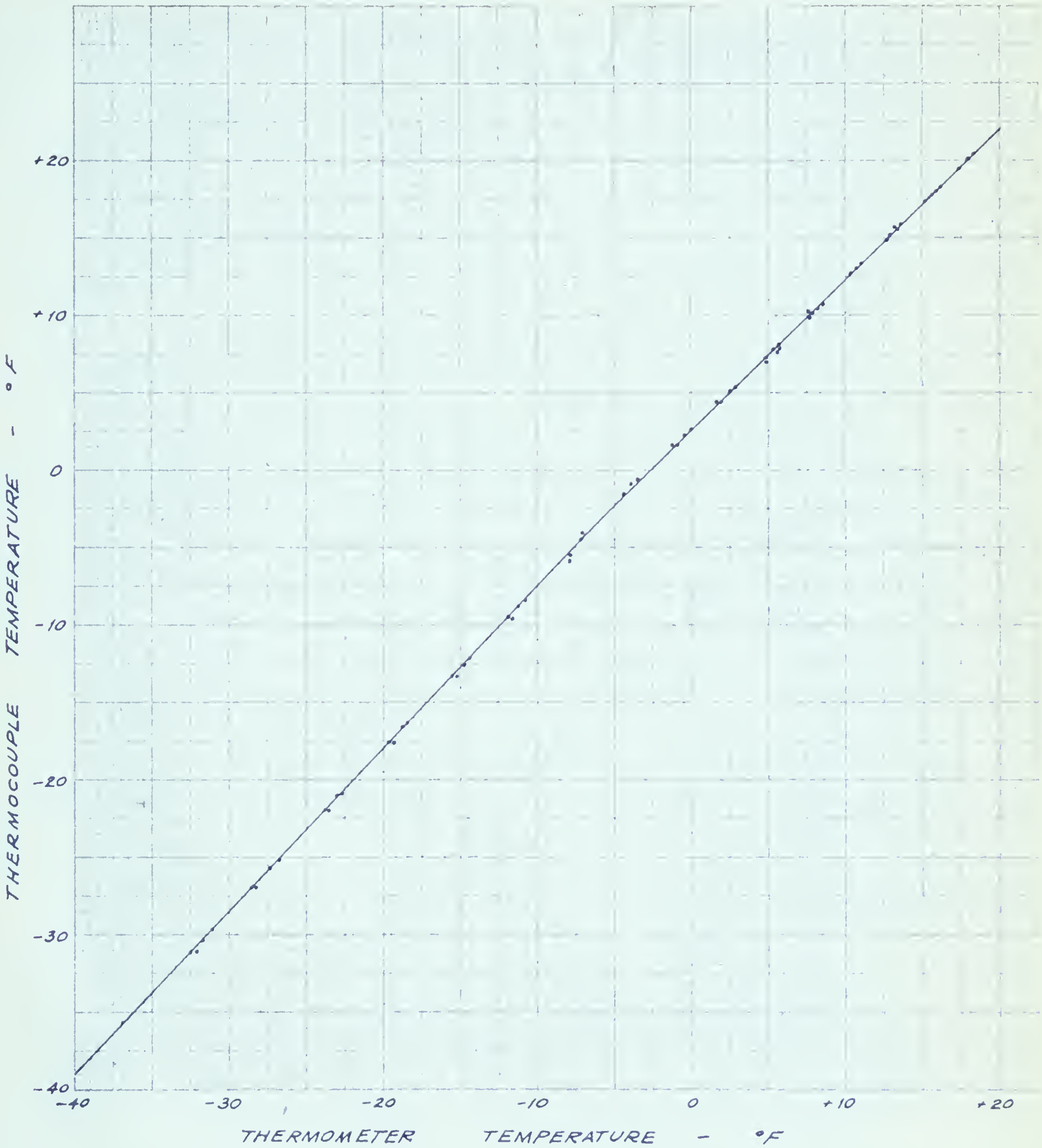
The partial immersion thermometer was mounted on a stand and thermocouples were secured at the bulb of the thermometer. The bulb was immersed in acetone contained in a flask which in turn was suspended in a second flask filled with acetone. An agitator was provided for each flask, and the exterior flask was insulated with fibre glass. Photograph 7 shows the apparatus with the insulation removed.

The pair of flasks were removed from the assembly, placed into the temperature control cabinet, and brought to a temperature of -40°F. The apparatus was re-assembled and thermometer and thermocouple readings were taken simultaneously as the temperature gradually rose to ambient. The acetone in the inner and outer flasks was

PHOTOGRAPH 7. Thermocouple Calibration Apparatus

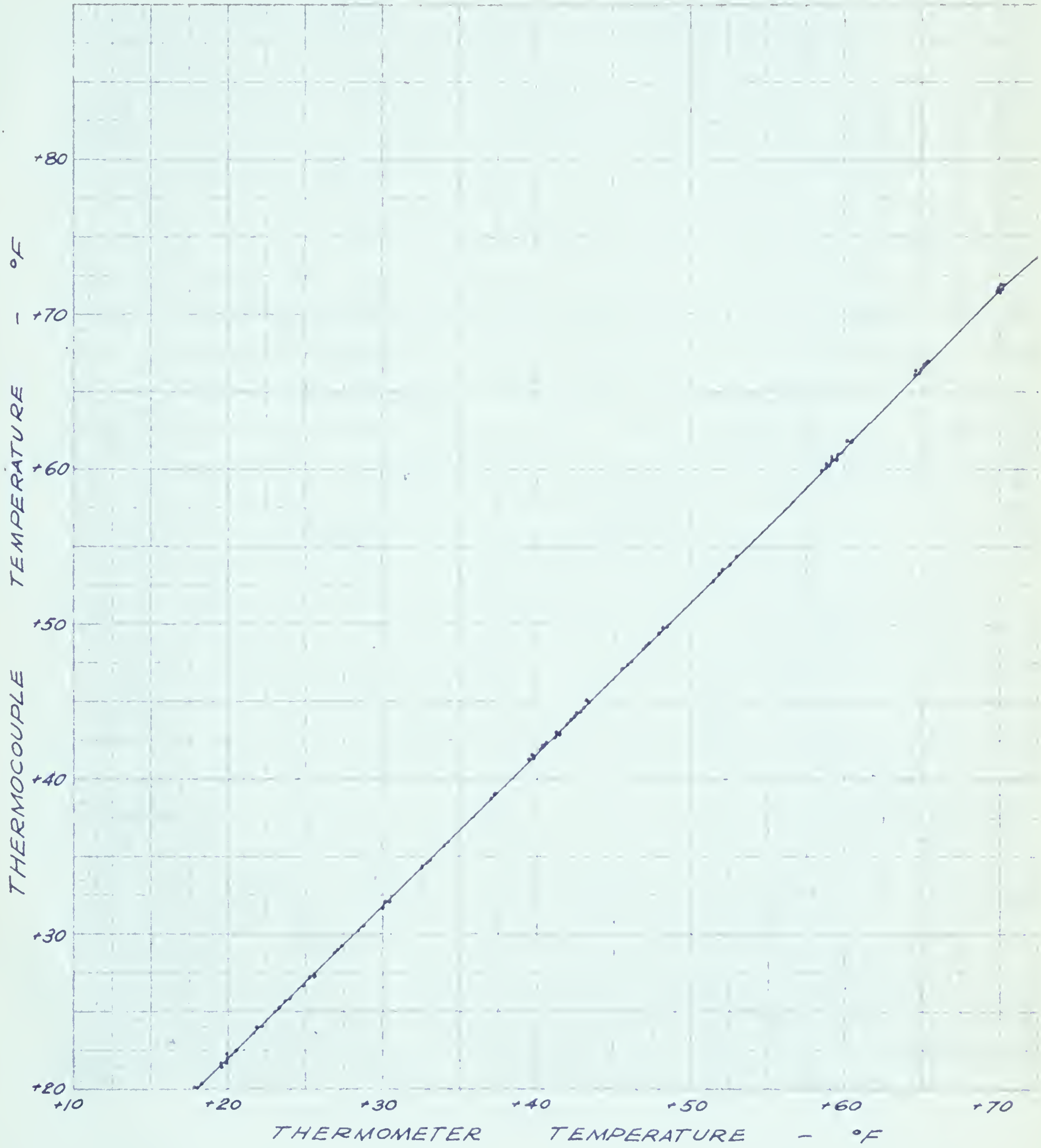
vigorously agitated before each reading. Similar procedure was followed to obtain readings above ambient temperature.

The thermometer readings were converted from Centigrade to Fahrenheit. The results are shown graphically in Figures 36, 37, and 38.



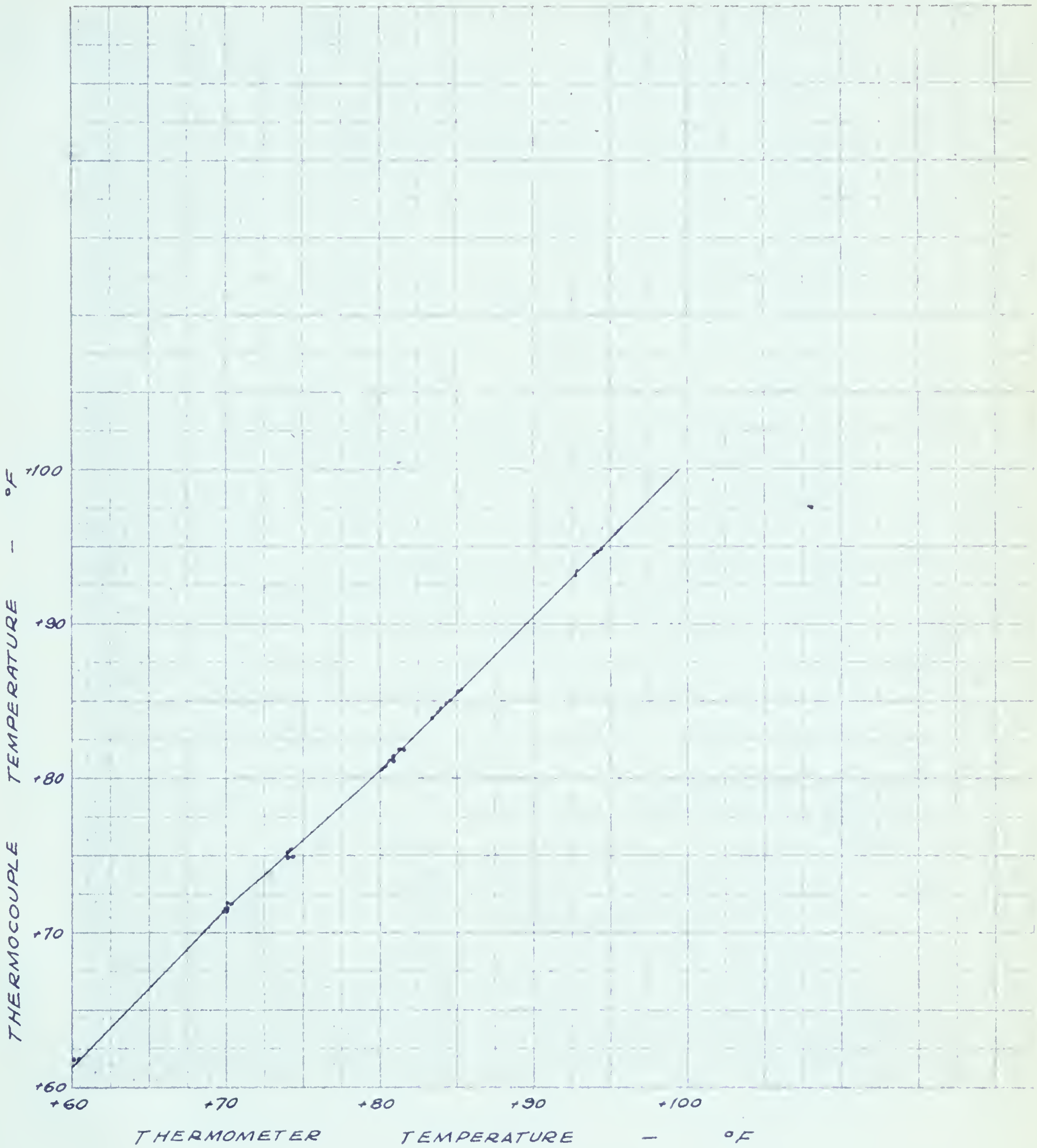
THERMOCOUPLE CALIBRATION CURVE 1

FIGURE 36



THERMOCOUPLE CALIBRATION CURVE 2

FIGURE 37



THERMOCOUPLE CALIBRATION CURVE 3

FIGURE 38